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Shao et al.

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(54) **METHODS AND SYSTEMS FOR CHARACTERIZING CONCEPT DRAWINGS AND ESTIMATING THREE-DIMENSIONAL INFORMATION THEREFROM**

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G06T 17/10	(2006.01)

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(52) **U.S. Cl.**

CPC ***G06K 9/481*** (2013.01); ***G06K 9/00476*** (2013.01); ***G06K 9/224*** (2013.01); ***G06T 7/0063*** (2013.01); ***G06T 17/10*** (2013.01); *G06T 2200/08* (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,239,314	B2	7/2007	Johnston	
2006/0274063	A1 *	12/2006	Grandine et al.	345/420

(Continued)

OTHER PUBLICATIONS

Ulupinar, F.; Nevatia, R., "Shape from contour: straight homogeneous generalized cylinders and constant cross section generalized cylinders," Pattern Analysis and Machine Intelligence, IEEE Transactions on , vol. 17, No. 2, pp. 120, 135, Feb. 1995.*

(Continued)

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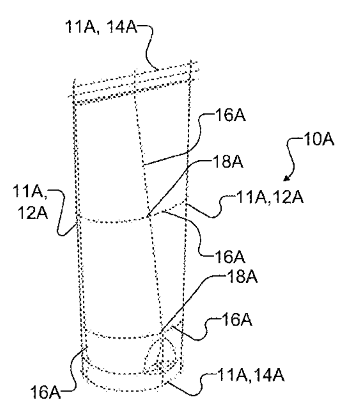
(57) **ABSTRACT**

Methods for characterizing two-dimensional concept drawings are disclosed. The concept drawings comprise cross-sections intersecting at cross-hairs. The method comprises: determining, for each cross-section: a plane on which the cross-section is located, the plane having a normal vector in a three-dimensional coordinate system; and, for each cross-hair on the cross-section, a tangent vector in the three-dimensional coordinate system which is tangent to the cross-section at the cross-hair. For each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, one or more constraints are satisfied, the constraints comprising: the normal vector n_i of the plane on which the i^{th} cross-section is located is at least approximately orthogonal to the normal vector n_j of the plane on which the j^{th} cross-section is located; and the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair is at least approximately orthogonal to the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair.

23 Claims, 6 Drawing Sheets



(51) **Int. Cl.**

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G06K 9/22	(2006.01)
G06K 9/00	(2006.01)
G06K 9/48	(2006.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2008/0246762	A1*	10/2008	Ogata et al.	345/420
2010/0220099	A1*	9/2010	Maekawa et al.	345/419
2014/0229143	A1*	8/2014	Cohen-Or et al.	703/1

OTHER PUBLICATIONS

McCrae, James, Karan Singh, and Niloy J. Mitra. "Slices: a shape-proxy based on planar sections." ACM Trans. Graph. 30.6 (Aug. 2011): 168.*
Kazmi, I.K.; Lihua You; Jian Jun Zhang, "A Survey of Sketch Based Modeling Systems," Computer Graphics, Imaging and Visualization (CGIV), 2014 11th International Conference on , vol., no., pp. 27, 36, Aug. 6-8, 2014.*
Ulupinar, Fatih, and Ramakant Nevatia. "Shape from contour: Straight homogeneous generalized cylinders and constant cross section generalized cylinders." Pattern Analysis and Machine Intelligence, IEEE Transactions on17.2 (1995): 120-135.*
Wong, K. K. Y., Paulo RS Mendonça, and Roberto Cipolla. "Reconstruction of surfaces of revolution from single uncalibrated views." Proceedings of the British Machine Vision Conference. vol. 1. 2002.*
Shao et al., "CrossShade: Shading Concept Sketches Using Cross-Section Curves", published online Jun. 1, 2012.
Andre et al., "Single-view sketch based modeling", 2011, In Proc. Symp. on Sketch-Based Interfaces and Modeling.
Andre et al., "Crosssketch: freeform surface modeling with details", 2007. In Proc. Symp. on Sketch-Based Interfaces and Modeling, 45-52.
Bae et al., "ILoveSketch: as-natural-as-possible sketching system for creating 3d curve models", 2008, In Proc. User Interface Software and Technology.
Biard et al., "Construction of rational surface patches bounded by lines of curvature", 2010, Comput. Aided Geom. Des. 27, 359-371.
Cole et al., "How well do line drawings depict shape?", 2009, ACM Trans. on Graph. (Proc. of SIGGRAPH) 28, 3.
Ecker et al., "Shape from planar curves: A linear escape from flatland", 2007, In IEEE Computer Vision and Pattern Recognition.
Farin et al., "Discrete coons patches", 1999, Computer Aided Geometric Design 16 (August), 691-700.
Finch et al., "Freeform vector graphics with controlled thin-plate splines", 2011, ACM Trans. on Graph. (Proc. SIGGRAPH Asia) 30.
Gangnet et al., "Incremental computation of planar maps", 1989, SIGGRAPH 23 (July), 345-354.
Gingold et al., "Structured annotations for 2D-to-3D modeling", 2009, ACM Trans. on Graph. (Proc. SIGGRAPH Asia) 28, 5.
Gooch et al., "A non-photorealistic lighting model for automatic technical illustration", 1998, SIGGRAPH, 447-452.
Igarashi et al., "Teddy: a sketching interface for 3d freeform design", 1999, SIGGRAPH.
Johnston, S. F., "Lumo: illumination for cel animation", 2002, In Proc. Symp. on Non-Photorealistic Animation and Rendering.
Joshi, P. et al., "Repoussé: Automatic inflation of 2d artwork", 2008, In Proc. of Sketch Based Interfaces and Modeling.
Knill, D. C., Perception of surface contours and surface shape: from computation to psychophysics, 1992, Journal of Optical Society of America 9, 9, 1449-1464.
Koenderink et al., "Surface perception in pictures", 1992, Perception & Psychophysics, 487-496.
Malik, J., "Interpreting line drawings of curved objects", 1987, International Journal of Computer Vision 1, 1, 73-103.
Mamassian et al., "Observer biases in the 3D interpretation of line drawings", 1998, Vision research 38, 18, 2817-2832.
McCrae et al., "Slices: A shape-proxy based on planar sections", 2011, ACM Trans. on Graph. (Proc. SIGGRAPH Asia) 30, 6.
Nasri et al., "Filling N -Sided Regions by Quad Meshes for Subdivision Surfaces", 2009, Computer Graphics Forum 28, 6 (Sept.), 1644-1658.
Nealen et al., "Fibermesh: designing freeform surfaces with 3d curves", 2007, ACM Trans. on Graph. (Proc. SIGGRAPH) 26 (July).
Okabe et al., "Single-view relighting with normal map painting", 2006, In Proc. Pacific Graphics, 27-34.
Olsen et al., "Sketch-based modeling: A survey", 2009, Computers & Graphics 33.
Orzan et al., "Diffusion curves: A vector representation for smooth-shaded images", 2008, ACM Trans. on Graph. (Proc. SIGGRAPH) 27.
Schmidt et al., "On expert performance in 3D curve-drawing tasks", 2009, In Proc. Symp. Sketch-Based Interfaces and Modeling.
Schmidt et al., "Analytic drawing of 3d scaffolds", 2009, ACM Trans. on Graph. (Proc. SIGGRAPH Asia) 28, 5.
Stevens, K. A., "The visual interpretation of surface contours", 1981, Artificial Intelligence 17.
Sýkora et al., "Lazy-Brush: Flexible painting tool for hand-drawn cartoons", 2009, Computer Graphics Forum (Proc. EUROGRAPHICS) 28, 2.
Winnemöller et al., "Texture design and draping in 2d images", 2009, Computer Graphics Forum (Proc. Symp. on Rendering) 28, 4.
Wu et al., "Shapepalettes: interactive normal transfer via sketching", 2007, ACM Trans. on Graph. (Proc. of SIGGRAPH) 26.
Zhang et al., "Single view modeling of free-form scenes", 2002, In IEEE Computer Vision and Pattern Recognition, 990-997.
Lipson et al., "Optimization-based reconstruction of a 3d object from a single freehand line drawing", 1996, Computer-Aided Design 28, 651-663.

* cited by examiner

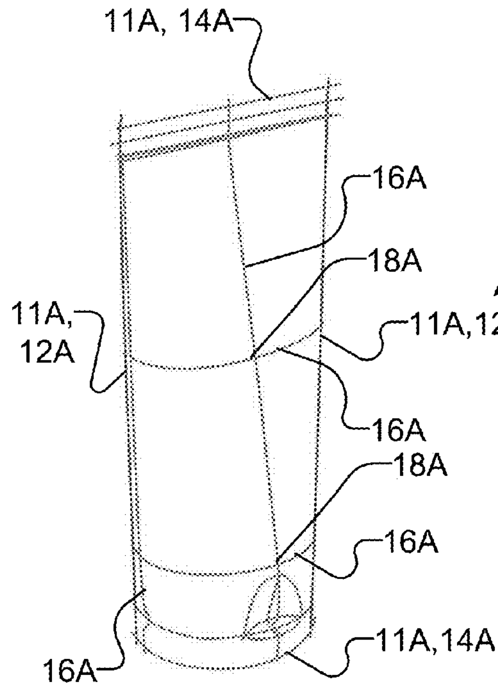

FIGURE 1A

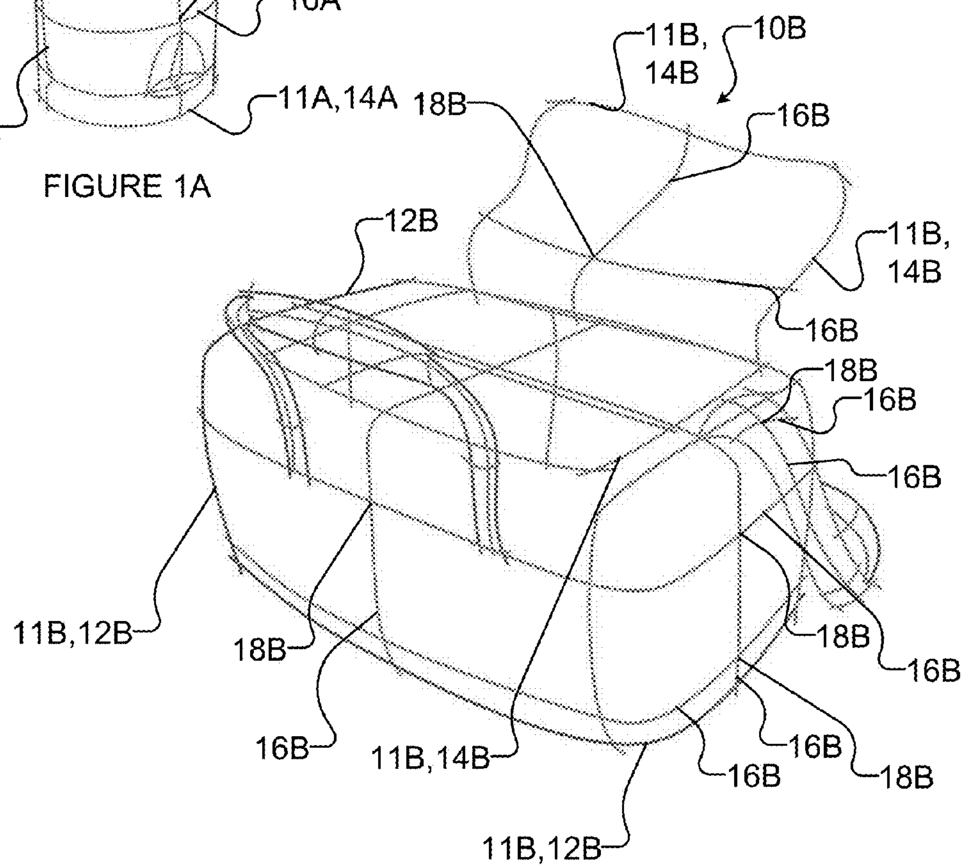

FIGURE 1B

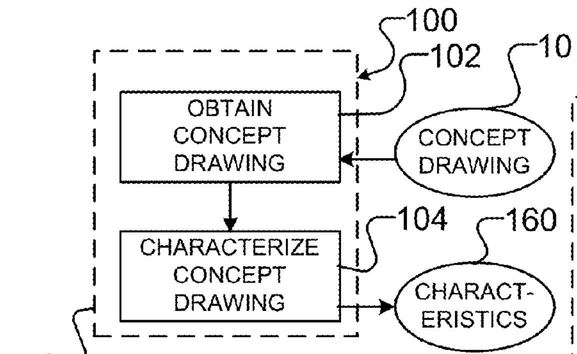

FIGURE 2A

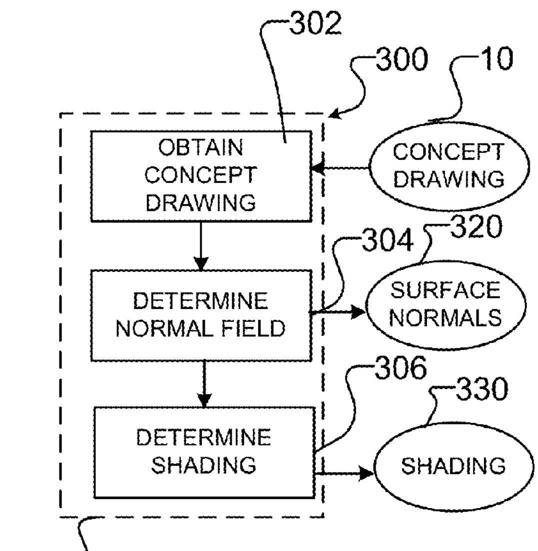

FIGURE 2C

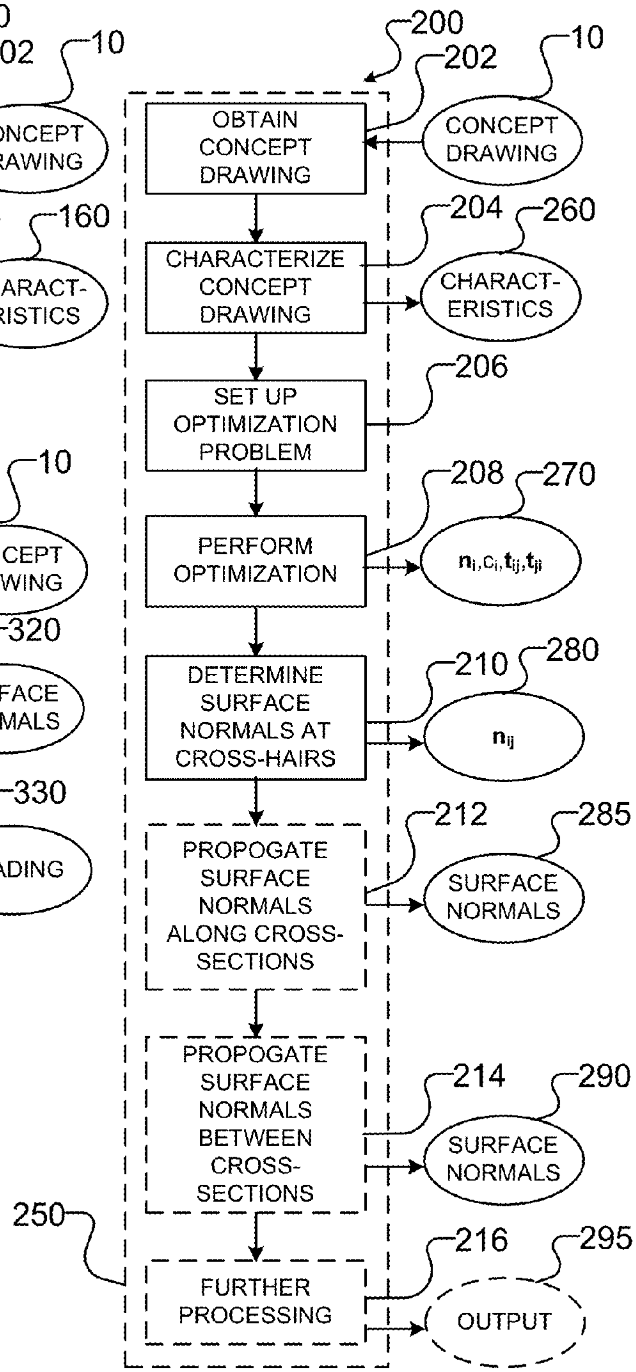

FIGURE 2B

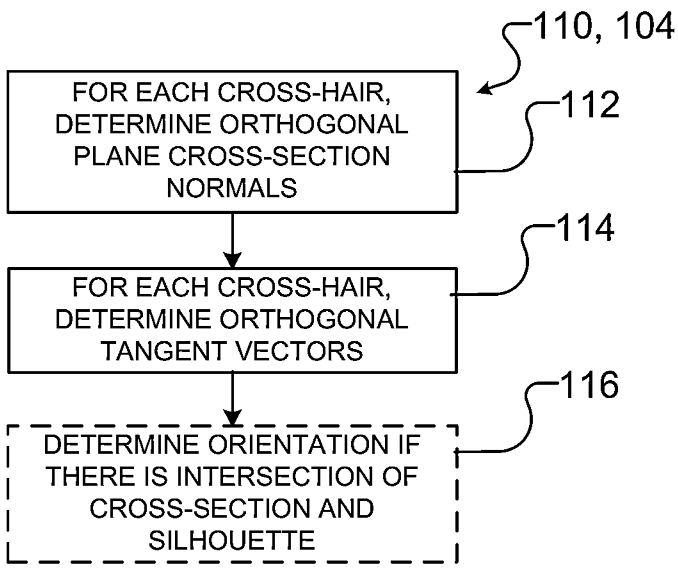

FIGURE 3A

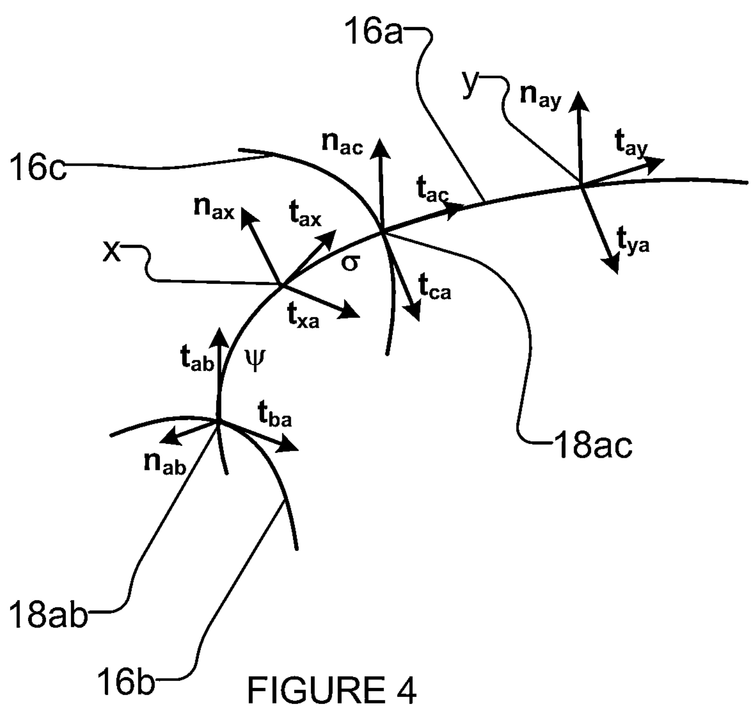

FIGURE 4

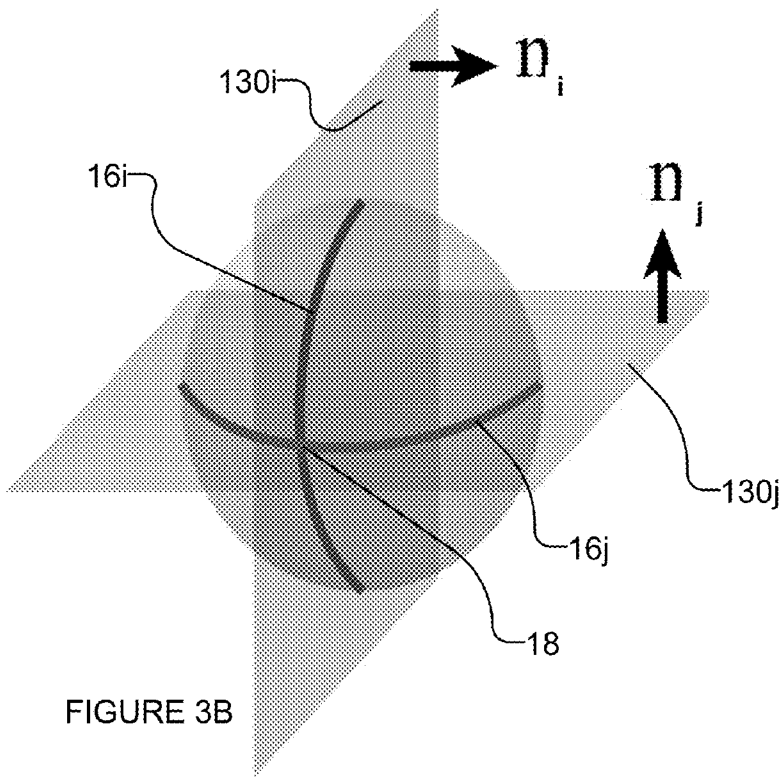

FIGURE 3B

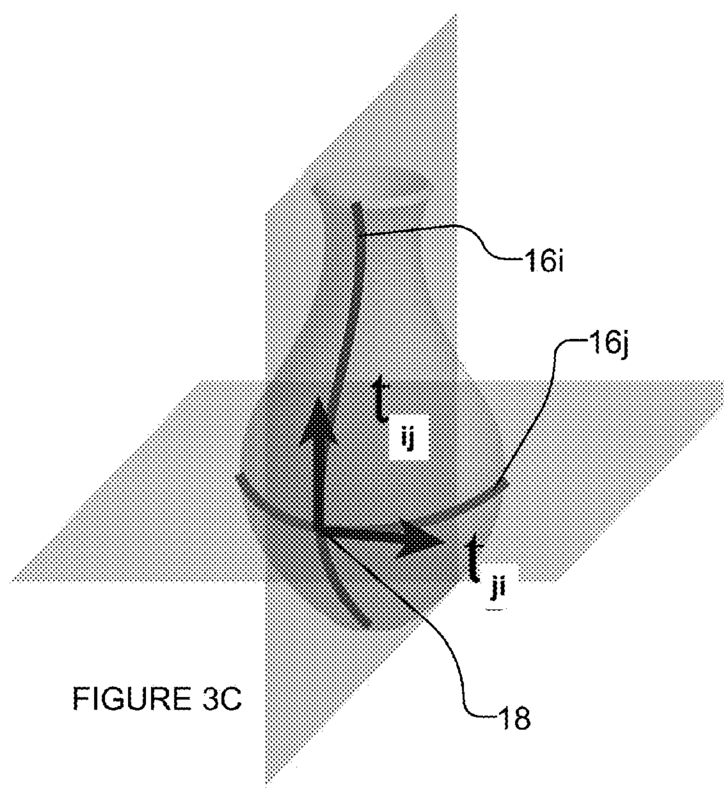

FIGURE 3C

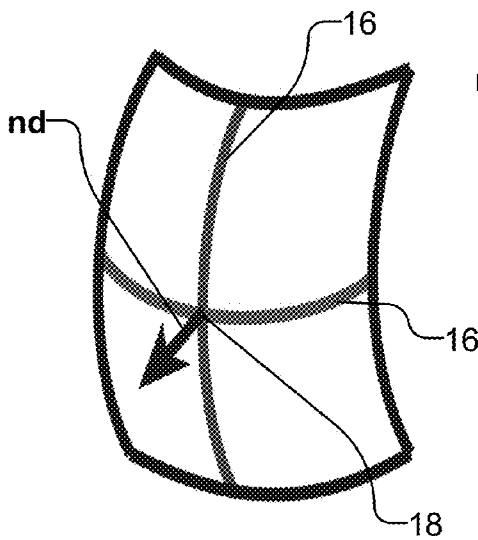

FIGURE 3D

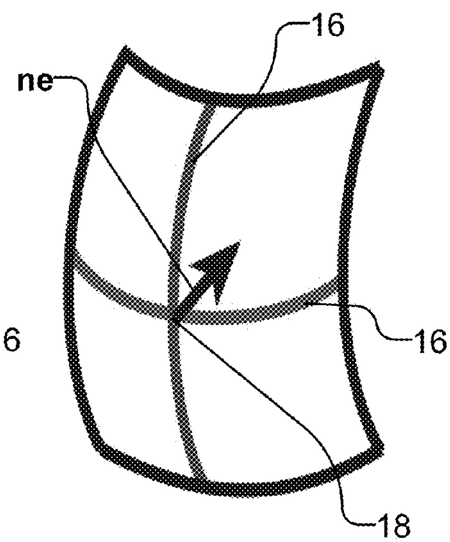

FIGURE 3E

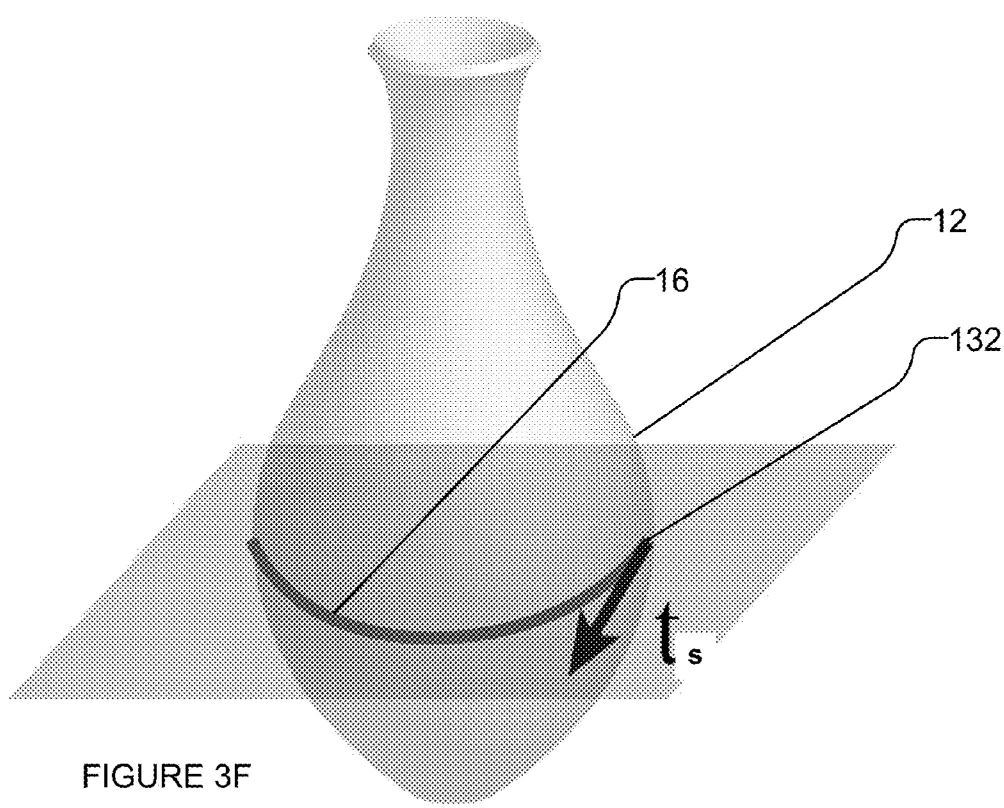

FIGURE 3F

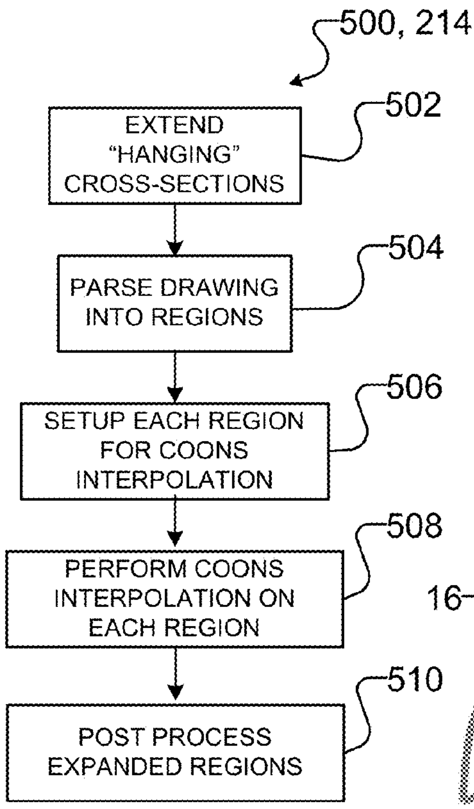

FIGURE 5A

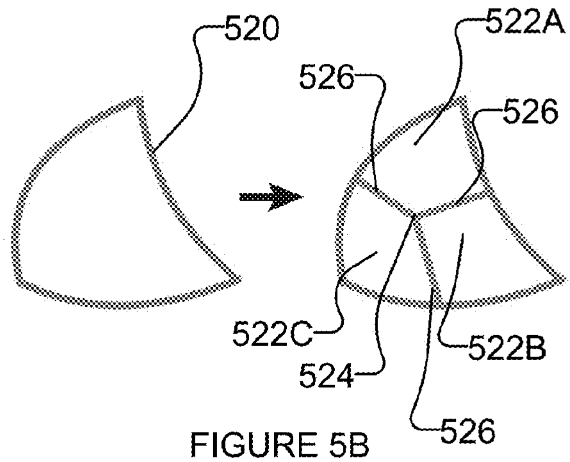

FIGURE 5B

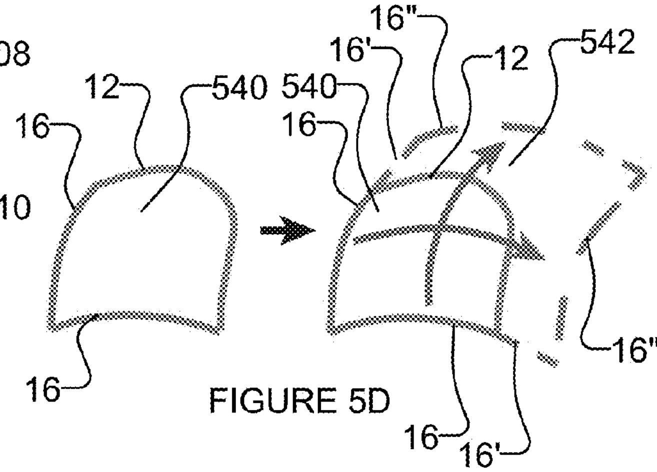

FIGURE 5D

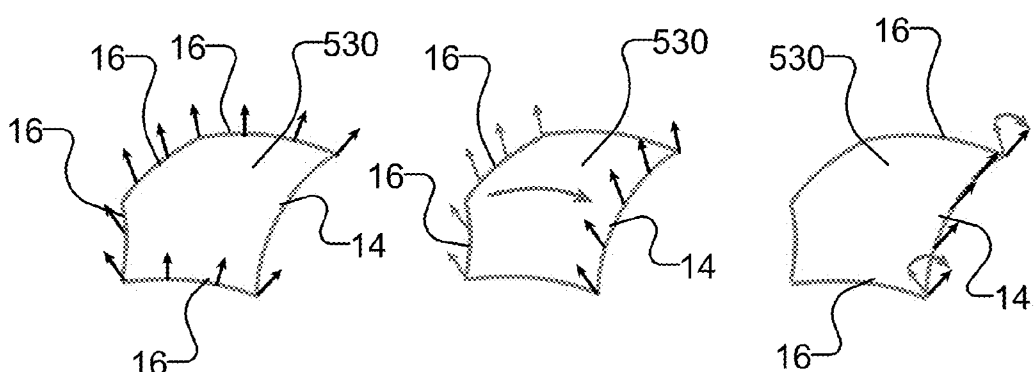

FIGURE 5C

METHODS AND SYSTEMS FOR CHARACTERIZING CONCEPT DRAWINGS AND ESTIMATING THREE-DIMENSIONAL INFORMATION THEREFROM

RELATED APPLICATIONS

This application is claims the benefit of the priority of U.S. application No. 61/821,152 filed 8 May 2013 and No. 61/829,864 filed 31 May 2013, both of which are hereby incorporated herein by reference.

TECHNICAL FIELD

This application relates to concept drawings or concept sketches as represented on a computer or similar processing environment. Particular embodiments provide methods and systems for characterizing concept drawings as represented on a computer or similar processing environment. Particular embodiments provide methods and systems for generating three-dimensional normal vector fields corresponding to two-dimensional concept drawings.

BACKGROUND

Concept drawings (also referred to as concept sketches) are used by artists and designers to convey the shapes of objects. Examples of concept drawings **10**A and **10**B (collectively, concept drawings **10**) are shown in FIGS. **1**A and **1**B (collectively, FIG. **1**). Concept drawing **10**A of FIG. **1**A is drawing of a hand cream container and concept drawing **10**B of FIG. **1**B is a drawing of a sports bag. The hand cream container and the sports bag may be referred to herein as the objects underlying concept drawings **10**A, **10**B, respectively. Concept drawings (whether drawn on paper or represented in a computer) typically comprise a plurality of two-dimensional curves which are used by the artist or designer to convey to observers three-dimensional information about the objects underlying the drawings. Concept drawings **10** typically include a number of types of two-dimensional curves. Boundary curves **11**A, **11**B (collectively, boundary curves **11**) demarcate parts of the object underlying concept drawings **10**. Boundary curves **11** may include smooth silhouette curves (or, for brevity, silhouettes) **12**A, **12**B (collectively, silhouettes **12**) and sharp boundary curves (or, for brevity, sharp boundaries) **14**A, **14**B (collectively, sharp boundaries **14**). Silhouettes **12** may demarcate transitions between visible and hidden parts of a smooth surface and may be dependent on the views depicted in concept drawings **10**. In mathematical terms, silhouettes **12** may demarcate parts of concept drawings **10** where the surface normal of the objects underlying the concept drawings **10** transitions from facing toward the viewer to facing away from the viewer. Sharp boundaries **14** can demarcate ends of surfaces, junctions between different parts of objects, sharp bends on surfaces, discontinuous transitions and/or the like. In some views and/or for some objects boundary curves **11** can be both silhouettes **12** and sharp boundaries **14** or such silhouettes **12** and sharp boundaries **14** may overlap.

In addition to boundary curves, artists and designers typically use cross-section curves (or, for brevity, cross-sections) **16**A, **16**B (collectively, cross-sections **16**) which aid in the drawing of concept sketches **10** and in the viewer's interpretation of the three-dimensional appearance of objects underlying concept sketches **10**. The intersections of cross-sections **16** may be referred to as cross-hairs **18**. When drawn in concept sketches (on paper or on computer representations), cross-sections **16** are only two-dimensional. However, cross-sections **16** are used to convey three-dimensional information about the objects underlying the concept drawings by depicting intersections of imagined three-dimensional surfaces with three-dimensional planes. Cross-sections **16** and cross-hairs **18** carry important perceptual information for viewers and are typically drawn at or near locations where they maximize (or at least improve) the clarity of concept sketches **10**.

There is a general desire to characterize concept drawings **10**. Such characterization may comprise generating three-dimensional information based on two-dimensional concept drawings **10**.

The foregoing examples of the related art and limitations are intended to be illustrative and not exclusive. Other limitations of the related art will become apparent to those of skill in the art upon a reading of the specification and a study of the drawings.

SUMMARY

The following embodiments and aspects thereof are described and illustrated in conjunction with systems, tools and methods which are meant to be exemplary and illustrative, not limiting in scope. In various embodiments, one or more of the above-described problems have been reduced or eliminated, while other embodiments are directed to other improvements.

One aspect of the invention provides a method for characterizing a concept drawing comprising a plurality of cross-hairs, each cross-hair comprising an intersection of two corresponding cross-sections. The characterization method may comprise generating three-dimensional mathematical characteristics about an object underlying the concept drawing based on the two-dimensional concept drawing. The characterization method may be implemented, at least in part, by one or more computers or suitably configured processors. The characterization method may comprise analyzing the plurality of cross-hairs. Analyzing the plurality of cross-hairs may comprise, for each cross-hair: defining the two corresponding cross-sections to be on two corresponding planes having cross-section normal vectors n_i, n_j in a three-dimensional coordinate system and requiring that the two corresponding planes are approximately orthogonal to one another ($|n_i \cdot n_j| \leq \epsilon$), where ϵ is a positive number close to zero and is a parameter used to accommodate error in the concept drawing; defining tangent vectors along the two corresponding cross-sections in the three-dimensional coordinate system and requiring that the two tangent vectors of the two corresponding cross-sections at the location of the cross-hair (t_{ij}, t_{ji}) are approximately orthogonal to one another ($|t_{ij} \cdot t_{ji}| \leq \gamma$) where γ is a positive number close to zero and is a parameter used to accommodate error in the concept drawing.

In some embodiments, the characterization method may comprise, in circumstances where the concept drawing comprises a silhouette and one of the cross-sections intersects the silhouette, requiring that a tangent vector on the cross-section at the intersection of the cross-section and the silhouette (t_s) must have a depth (z) component that extends out of a view plane of the concept drawing and toward the viewer in the three-dimensional coordinate system.

Another aspect of the invention provides a method for generating a normal vector field that represents a surface of an object underlying a concept drawing, the concept drawing comprising a plurality of cross-sections and a plurality of cross-hairs, each cross-hair comprising an intersection of two corresponding cross-sections. The normal vector generating method is implemented, at least in part, by one or more computers or suitably configured processors. The method comprises performing a constrained optimization which minimizes an objective function subject to one or more constraints to solve for: a plurality of cross-section normal vectors, each cross-section normal vector n_i corresponding to an i^{th} one of the cross-sections and normal to an i^{th} plane defined in a three-dimensional coordinate system and such that the i^{th} plane includes the i^{th} one of the cross-sections; a plurality of tangent vectors in the three-dimensional coordinate system, each tangent vector t_{ij} corresponding to an ij^{th} one of the cross-hairs and comprising a tangent to the i^{th} one of the cross-sections at a location, in the three-dimensional coordinate system, of the ij^{th} cross-hair where the i^{th} one of the cross-sections intersects the j^{th} one of the cross-sections; and a plurality of offset values, each offset value c_i representing a location of the i^{th} plane in the three-dimensional coordinate system (e.g. c_i may represent a closest distance from the origin of the three-dimensional coordinate system to the i^{th} plane). The method comprises: generating a normal vector field comprising a plurality of cross-hair surface normal vectors in the three-dimensional coordinate system, each cross-hair surface normal vector n_{ij} located at the location, in the three-dimensional coordinate system, of the ij^{th} cross-hair where the i^{th} one of the cross-sections intersects the j^{th} one of the cross-sections and oriented orthogonally to the surface of the object underlying the concept drawing at the location of the ij^{th} cross-hair, wherein generating the plurality of cross-hair surface normal vectors is based at least in part on one or more of the plurality of cross-section normal vectors, the plurality of tangent vectors and the plurality of offset values. The method may comprise propagating the cross-hair surface normal vectors to locations away from the cross-hairs to further populate the normal vector field at locations away from the cross-hairs.

Another aspect of the invention provides a method for characterizing an object underlying a concept drawing, the concept drawing comprising a plurality of cross-sections and a plurality of cross-hairs, each cross-hair comprising an intersection of two corresponding cross-sections. The characterization method comprises determining parameters for a plurality of planes in a three-dimensional coordinate system, each of the planes including a corresponding one of the cross-sections. The characterization method may optionally involve determining an estimate of the curves of the cross-sections in the three-dimensional coordinate system wherein the curve for each cross-section in the three-dimensional coordinate system is located on the plane corresponding to the cross-section. The characterization method is implemented, at least in part, by one or more computers or suitably configured processors. The method comprises performing a constrained optimization which minimizes an objective function subject to one or more constraints to solve for: a plurality of cross-section normal vectors, each cross-section normal vector n_i corresponding to an i^{th} one of the cross-sections and normal to an i^{th} plane defined in a three-dimensional coordinate system and such that the i^{th} plane includes the i^{th} one of the cross-sections; a plurality of tangent vectors in the three-dimensional coordinate system, each tangent vector t_{ij} corresponding to an ij^{th} one of the cross-hairs and comprising a tangent to the i^{th} one of the cross-sections at a location, in the three-dimensional coordinate system, of the ij^{th} cross-hair where the i^{th} one of the cross-sections intersects the j^{th} one of the cross-sections; and a plurality of offset values, each offset value c_i representing a location of the i^{th} plane in the three-dimensional coordinate system (e.g. c_i may represent a closest distance from the origin of the three-dimensional coordinate system to the i^{th} plane).

In some embodiments, the objective function and/or the one or more constraints are based on mathematical characteristics of concept drawings which relate to how the concept drawings are commonly perceived to represent three-dimensional objects. In some embodiments, the objective function and/or the one or more constraints is based on the characteristic that, for each cross-hair, the cross-section normal vectors n_i, n_j of the two corresponding cross-sections that intersect at the cross-hair are approximately orthogonal to one another ($|n_i \cdot n_j| \leq \epsilon$), where ϵ is a positive number close to zero and is a parameter used to accommodate error in the concept drawing. In some embodiments, the objective function and/or the one or more constraints is based on the characteristic that, for each cross-hair, the tangent vectors t_{ij} and t_{ji} of the two corresponding cross-sections at the location of the cross-hair are approximately orthogonal to one another ($|t_{ij} \cdot t_{ji}| \leq \gamma$), where γ is a positive number close to zero and is a parameter used to accommodate error in the concept drawing.

In some embodiments, the objective function and/or the one or more constraints is based at least in part on $t_{ij} \times n_j$ and $t_{ji} \times n_i$, where, for each cross-hair, n_i, n_j represent the cross-section normal vectors of the two corresponding cross-sections and t_{ij} and t_{ji} the tangent vectors of the two corresponding cross-sections at the location of the cross-hair. In some embodiments, the objective function and/or the one or more constraints is based at least in part on the sum $\Sigma[(t_{ij}^z)^2+(t_{ji}^z)^2]$ over the plurality of cross-hairs, where, for each cross-hair, t_{ij}^z and t_{ji}^z are the z-components of the tangent vectors t_{ij} and t_{ji} of the two corresponding cross-sections at the location of the cross-hair and the z-direction orthogonal to a view plane of the concept drawing.

In some embodiments, in circumstances where the concept drawing comprises a silhouette and a particular cross-section intersects the silhouette, performing the constrained optimization may comprise assuming that a tangent vector on the particular cross-section at the intersection of the cross-section and the silhouette (t_s) has a depth (z) component that extends out of a view plane of the concept drawing and toward the viewer in the three-dimensional coordinate system.

Some embodiments provide systems where steps of the methods described herein are performed by one or more computers and/or one or more suitably configured processors.

Some embodiments provide computer program products comprising a set of instructions embodied on a non-transitory computer readable medium, the instructions when executed by a processor, cause the processor to perform the methods described herein.

In addition to the exemplary aspects and embodiments described above, further aspects and embodiments will become apparent by reference to the drawings and by study of the following detailed descriptions.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments are illustrated in referenced figures of the drawings. It is intended that the embodiments and figures disclosed herein are to be considered illustrative rather than restrictive.

FIGS. **1**A and **1**B are representative examples of concept drawings.

FIG. **2**A is a block diagram of a method for characterizing a concept drawing according to a particular embodiment.

FIG. **2**B is a block diagram of a method for generating a normal vector field that represents a surface of an object underlying a concept drawing according to a particular embodiment.

FIG. 2C is a block diagram of a method for generating a normal vector field that represents a surface of an object underlying a concept drawing and generating representative shading for the object underlying the concept drawing based on the normal vector field according to a particular embodiment.

FIG. 3A is a characterization method according to a particular embodiment which may be used as a part of the FIG. 2A characterization method.

FIG. 3B is an illustrative drawing showing the orthogonality of cross-section normal vectors according to the FIG. 3A characterization method.

FIG. 3C is an illustrative drawing showing the orthogonality of tangent vectors of cross-sections at the locations of cross-hairs according to the FIG. 3A characterization method.

FIGS. 3D and 3E are illustrative drawing showing the ambiguity in surface direction based on intersecting cross-sections. FIG. 3F is an illustrative drawing showing the directionality of a tangent vector at a location in an immediate vicinity of the intersection between a cross-section and a silhouette which may be used in the FIG. 3A characterization method.

FIG. 4 is an illustrative drawing showing how surface normal vectors may be propagated along a cross-section.

FIG. 5A is a block diagram of a method for propagating surface normal vectors to regions off of cross-sections that may be used in the method of FIG. 2B. FIGS. 5B, 5C and 5D are schematic drawings which show how regions are processed to make them suitable for Coons interpolation.

DESCRIPTION

Throughout the following description specific details are set forth in order to provide a more thorough understanding to persons skilled in the art. However, well known elements may not have been shown or described in detail to avoid unnecessarily obscuring the disclosure. Accordingly, the description and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

One aspect of the invention provides a method for characterizing a concept drawing comprising a plurality of cross-hairs, each cross-hair comprising an intersection of two corresponding two-dimensional cross-sections. The characterization method may comprise generating three-dimensional mathematical characteristics about an object underlying the concept drawing based on the two-dimensional concept drawing. The characterization method is implemented, at least in part, by one or more computers or suitably configured processors. The characterization method may comprise analyzing the plurality of cross-hairs. Analyzing the plurality of cross-hairs may comprise, for each cross-hair: defining the two corresponding cross-sections to be on two corresponding planes having cross-section normal vectors n_i, n_j in a three-dimensional coordinate system and requiring that the two corresponding planes are approximately orthogonal to one another ($|n_i \cdot n_j| \leq \epsilon$), where ϵ is a positive number close to zero and is a parameter used to accommodate error in the concept drawing; defining tangent vectors along the two corresponding cross-sections in the three dimensional coordinate system and requiring that the two tangent vectors of the two corresponding cross-sections at the location of the cross-hair (t_{ij}, t_{ji}) are approximately orthogonal to one another ($|t_{ij} \cdot t_{ji}| \leq \gamma$) where γ is a positive number close to zero and is a parameter used to accommodate error in the concept drawing. The characterization method may optionally comprise, in circumstances where the concept drawing comprises a two-dimensional silhouette and one of the cross-sections intersects the silhouette, requiring that a tangent vector on the cross-section at the intersection of the cross-section and the silhouette (t_s) have a depth (z) component that extends out of a view plane of the concept drawing and toward the viewer in the three-dimensional coordinate system.

FIG. 2A is a block diagram of a method **100** for characterizing a concept drawing according to a particular embodiment. Characterization method **100** may be implemented, at least in part, by one or more computers or suitably configured processors **150**—shown in dashed lines in FIG. 2B. Characterization method **100** may comprise generating three-dimensional mathematical characteristics about an object underlying the concept drawing based on the two-dimensional concept drawing (e.g. based on the two-dimensional curves of the concept drawing). Method **100** starts in block **102** which comprises procuring a concept drawing **10** as input. In some embodiments, concept drawing **10** is received as input to computer system **150** (e.g. concept drawing **10** may be generated on paper and scanned or generated on some other computer and/or the like and may be provided to computer system **150** as input). In some embodiments, concept drawing may be generated in computer system **150** and may be generated using the same software as that which implements characterization method **100** or using different software (e.g. commercial drawing and/or sketching software (Adobe Illustrator, Autodesk Sketchbook, Inkscape and/or the like) and/or the like).

Exemplary and non-limiting concept drawings **10** are illustrated in FIG. **1**. In the case of concept drawing **10**A of FIG. **1**A, the object underlying concept drawing **10**A is a hand cream container and the object underlying concept drawing **10**B is a sports bag. It will be appreciated that concept drawings **10** of FIGS. **1**A and **1**B are only representative examples and that method **100** may be used to characterize any suitable concept drawings and any suitable underlying objects. As discussed above, concept drawings **10** are two-dimensional drawings which comprise one or more two-dimensional boundary curves (which may include silhouettes **12** and sharp boundaries **14**). Concept drawings **10** also typically comprise one or more two-dimensional cross-sections **16**, used to try to convey three-dimensional information about the object underlying concept drawings **10** to viewers. In the case of characterization method **100**, the concept drawings procured in block **102** may comprise a plurality of cross-sections **16** and such cross-sections **16** may intersect one another at a plurality of cross-hairs **18**. As will be explained in more detail below, method **100** may characterize the block **102** input concept drawing based, at least in part, on its cross-hairs. In some cases, a block **102** input concept drawing may not have a plurality of cross-hairs **18**. In such cases, block **102** may reject the concept drawing and require that an artist manually add additional cross-sections **16** and/or cross-hairs **18**. In some embodiment, obtaining a concept drawing in block **102** may involve creating, editing or augmenting the concept drawing.

It is assumed, for the purposes of this description, that two-dimensional concept drawings **10** are defined in a plane referred to as the view plane. The view plane may be defined by the x and y-axes of a three-dimensional coordinate system and the z-axis may be defined to be the axis orthogonal to the view plane and in the view direction, where the positive z-direction is toward the viewer and the negative z-direction is away from the viewer. It will be appreciated that this definition of the axes of the three-dimensional coordinate system is selected to model three-dimensional space and is not unique.

Other three-dimensional coordinate system definitions could be envisaged to model three dimensional space.

It is assumed, for the purposes of explaining method **100**, that obtaining the block **102** concept drawing comprises determining the spatial location of boundary curves (silhouettes **12**, sharp boundaries **14**), cross-sections **16** and cross-hairs **18** in a two-dimensional spatial coordinate system. In some embodiments, this spatial location information may comprise part of the block **102** input (i.e. the data representative of the block **102** concept drawings may comprise this spatial location information prior to being received in block **102**). In some embodiments, this spatial location information may be generated in block **102**. By way of non-limiting example, the block **102** concept drawing spatial location information may be generated from vector drawing software, bit maps or hand-drawn sketches converted into vector formats, existing models, scanned three-dimensional models and/or the like). In general, the block **102** concept drawing spatial location information may come from or be generated from any suitable source. In some embodiments, block **102** may also involve characterizing the curves in the input concept drawing as being cross-sections **16**, silhouettes **12** or sharp boundaries **14**. In some embodiments, this curve characterization may be input to method **100** as part of block **102**. In some embodiments, block **102** may involve determining this curve characterization information via user input, using suitable heuristics, suitable estimation algorithms or otherwise.

Method **100** (FIG. **2**A) then proceeds to block **104** which involves characterizing the concept drawing obtained in block **102**. FIG. **3**A is a block diagram of a characterization method **110** suitable for use in block **104** of method **100**. Characterization method **110** is based on the inventors' study of how cross-sections **16** and cross-hairs **18** are used by artists and how cross-sections **16** and cross-hairs **18** are perceived by viewers. Characterization method **110** commences in block **112** which involves ascertaining a property (e.g. a three-dimensional property) about the pair of cross-sections **16** that intersect at each cross-hair **18** in the concept drawing. More particularly, for each cross-hair **18**, block **112** involves defining the two corresponding cross-sections **16** to be on two corresponding three-dimensional planes having cross-section normal vectors n_i, n_j in a three-dimensional coordinate system and requiring that the two corresponding planes are approximately orthogonal to one another—i.e. ($|n_i \cdot n_j| \approx 0$). In some embodiments, the two planes may be considered to be approximately orthogonal when:

$$|n_i \cdot n_j| \leq \epsilon \qquad (1)$$

where ϵ is a positive number close to zero and is a parameter which may be configurable and which may be used to accommodate error in the concept drawing.

Block **112** may be better understood using FIG. **3**B as an exemplary reference. FIG. **3**B shows a pair of cross-sections **16***i*, **16***j* which intersect at a cross-hair **18**. Each of cross-sections **16***i*, **16***j* is characterized as being located on a corresponding plane **130***i*, **130***j* in a three-dimensional coordinate system, where planes **130***i*, **130***j* have normal vectors n_i, n_j respectively in the three-dimensional coordinate system. Block **112** requires that the normal vectors n_i, n_j for each cross-hair **18** be at least approximately orthogonal to one another.

Characterization method **110** then proceeds to block **114**. Block **114** involves ascertaining a property about the pair of cross-sections **16** that intersect at each cross-hair **18** in the concept drawing. More particularly, for each cross-hair **18**, block **114** involves: defining tangent vectors along the two corresponding cross-sections **16** in the three dimensional coordinate system; and requiring that the two tangent vectors of the two corresponding cross-sections **16** at the location of the cross-hair **18** (t_{ij}, t_{ji}) are at least approximately orthogonal to one another—i.e. $|t_{ij} \cdot t_{ji}| \approx 0$, where t_{ij} is the tangent to the i^{th} cross-section **16** at the location where the i^{th} cross-section **16** forms a cross-hair **18** with the j^{th} cross-section **16** and t_{ji} is the tangent to the j^{th} cross-section **16** at the location where the j^{th} cross-section **16** forms a cross-hair **18** with the i^{th} cross-section **16**. In some embodiments, the two tangent vectors may be considered to be approximately orthogonal when:

$$|t_{ij} \cdot t_{ji}| \leq \gamma \qquad (2)$$

where γ is a positive number close to zero and is a parameter which may be configurable and which may be used to accommodate error in the concept drawing.

Block **114** may be better understood using FIG. **3**C as an exemplary reference. FIG. **3**C shows a cross-hair **18** provided by the intersection of two cross-sections **16***i*, **16***j* and the tangent vectors to the two cross-sections **16***i*, **16***j* at the location of cross-hair **18**. More particularly, FIG. **3**C shows t_{ij} (i.e. the tangent to cross-section **16***i* at the location where cross-section **16***i* forms a cross-hair **18** with cross-section **16***j*) and t_{ji} (i.e. the tangent to cross-section **16***j* at the location where cross-section **16***j* forms a cross-hair **18** with cross-section **16***i*). Block **114** requires that the tangent vectors (t_{ij}, t_{ji}) for each cross-hair **18** be at least approximately orthogonal to one another.

Method **110** (FIG. **3**A) comprises an optional block **116** which may be used in circumstances where the input concept drawing includes a cross-section **16** that intersects with a silhouette **12**. Block **116** involves resolving an inherent ambiguity regarding the perception of shape based on intersecting cross-sections **16**. FIGS. **3**D and **3**E show this ambiguity. Cross-hair **18** and its corresponding cross-sections **16** are the same in both FIGS. **3**D and **3**E. In FIG. **3**D, surface normal vector n_d points downwardly so that the corresponding surface is interpreted as being convex. In contrast, in FIG. **3**E, surface normal vector n_e points upwardly so that the corresponding surface is interpreted as being concave.

This ambiguity can be resolved in circumstances where the input concept drawing includes a cross-section **16** that intersects with a silhouette **12**. A silhouette (also referred to as a smooth silhouette) is defined as a curve where the surface normal vector is orthogonal to the view direction (i.e. the z-axis). By definition, the surface in an immediate vicinity of silhouette **12** must be closer to the viewer than the silhouette **12** itself. This is demonstrated in FIG. **3**F which shows a cross-section **16** intersecting with a silhouette **12** at a location **132**. At a location on cross-section **16** and in reasonably close proximity to location **132**, the tangent vector t_s along cross-section **16** must have a depth (z) component that extends out of a view plane of the concept drawing and toward the viewer in the three-dimensional coordinate system. The directionality of the tangent vector t_s (toward the viewer) may be used as a basis for resolving the ambiguity in the directionality of the surface normal vector at, or reasonably close to, the intersection **132**, since the surface normal vector must also point toward the user and be orthogonal to t_s.

At the conclusion of characterization method **110** (FIG. **3**A), or characterization block **104** of method **100** (FIG. **2**A), the block **102** input concept drawing **10** (and its cross-sections **16**) have been characterized in a three-dimensional coordinate system to provide characteristics **160**. Characteristics **160** comprise: the block **112** properties of the cross-section normal vectors n_i, n_j which are normal to the planes on which the cross-sections **16** lie; the block **114** properties of the tangents t_{ij} and t_{ji} to the cross-sections **16** at the locations of the cross-hairs **18**; and, optionally, in circumstances where a cross-section **16** intersects a silhouette **12**, the block **116** directionality of the tangent vector t_s at a location in an immediate vicinity of this intersection.

Another aspect of the invention provides a method for generating a normal vector field that represents a surface of an object underlying a concept drawing. The normal vector generating method is implemented, at least in part, by one or more computers or suitably configured processors. The method may involve using some of the method **100** characterization information to perform a constrained optimization which minimizes an objective function subject to one or more constraints to solve for: a plurality of three-dimensional cross-section normal vectors, each cross-section normal vector n_i corresponding to an i^{th} one of the cross-sections and normal to an i^{th} plane defined in a three-dimensional coordinate system and such that the i^{th} plane includes the i^{th} one of the cross-sections; a plurality of three-dimensional tangent vectors in the three-dimensional coordinate system, each tangent vector t_{ij} corresponding to an ij^{th} one of the cross-hairs and comprising a tangent to the i^{th} one of the cross-sections at a location, in the three-dimensional coordinate system, of the ij^{th} cross-hair where the i^{th} one of the cross-sections intersects the j^{th} one of the cross-sections; and a plurality of offset values, each offset value c_i representing a location of the i^{th} plane (i.e. the plane that includes the i^{th} cross-section) in the three-dimensional coordinate system (e.g. c_i may represent a closest distance from the origin of the three-dimensional coordinate system to the i^{th} plane). The method comprises: generating a normal vector field comprising a plurality of cross-hair surface normal vectors in the three-dimensional coordinate system, each cross-hair surface normal vector n_{ij} located at the location, in the three-dimensional coordinate system, of the ij^{th} cross-hair where the i^{th} one of the cross-sections intersects the j^{th} one of the cross-sections and oriented orthogonally to the surface of the object underlying the concept drawing at the location of the ij^{th} cross-hair, wherein generating the plurality of cross-hair surface normal vectors is based at least in part on one or more of: the plurality of cross-section normal vectors, the plurality of tangent vectors and the plurality of offset values. The method may comprise propagating the cross-hair surface normal vectors to locations away from the cross-hairs to further populate the normal vector field at locations away from the cross-hairs.

FIG. **2**B is a block diagram of a method **200** for generating a normal vector field that represents a surface of an object underlying a concept drawing according to a particular embodiment. Normal vector generating method **200** is implemented, at least in part, by one or more computers or suitably configured processors **250**—shown in dashed lines in FIG. **2**B. Method **200** may comprise performing a constrained optimization which minimizes an objective function subject to one or more constraints, wherein the objective function and/or the constraints are based at least in part on concept drawing characterization of the type obtained in method **100** described above. As explained in more detail below, the output of this constrained optimization may include information that defines (in a three-dimensional coordinate system) one plane for each cross-sections **16** in the concept drawing, where each cross-section lies on its corresponding plane. The output of this constrained optimization may also include information desirable to obtain three-dimensional representations (i.e. representations in the three-dimensional coordinate system) of the tangent vectors to the cross-sections **16** at the locations of the cross-hairs **18** in the concept drawing. This information may comprise depth (z-direction) information in respect of the tangent vectors to the cross-sections **16** at the locations of the cross-hairs **18** in the concept drawing.

Method **200** commences in block **202** which involves procuring a concept drawing **10** as input. Block **202** of method **200** may be substantially similar to block **102** of method **100** described above. In some embodiments, concept drawing **10** is received as input to computer system **250** (e.g. concept drawing **10** may be generated on paper and scanned or generated on some other computer and/or the like and may be provided to computer system **250** as input). In some embodiments, concept drawing may be generated in computer system **250** and may be generated using the same software as method **200** or using different software (e.g. commercial drawing and/or sketching software and/or the like). Method **200** then proceeds to block **204** which involves characterizing the concept drawing obtained in block **202**. Block **204** may be substantially similar to block **104** of method **100** described above and may generate characteristics **260** similar to characteristics **160** described above. Method **200** then proceeds to block **206** which involves setting up an optimization problem. In some embodiments, the block **206** optimization problem set up is based on one or more additional observations about concept drawings and the manner in which concept drawings (and their cross-sections **16**) are used by designers/artists and interpreted by viewers.

In some embodiments, one observation used in the block **206** optimization problem set up is that designers/artists tend to use cross-sections **16** which are local geodesics. A cross-section **16** on a surface of an underlying object is a local geodesic if it defines the shortest distance between two points on the surface. Given the block **204** characterization, a cross-section **16** also lies in a plane (see block **112** and FIG. **3**B described above). It is known that if a surface curve lies on a plane and is a local geodesic, then the surface normal vector along the curve lies in the three-dimensional plane of that curve. Given the block **204** characterization, it may be proved that for an ij^{th} cross-hair **18** between an i^{th} cross-section **16** and a j^{th} cross-section **16** where the i^{th} cross-section **16** is a local geodesic, the cross-section normal n_i of the i^{th} plane which includes the i^{th} cross-section **16** is co-linear with the tangent vector t_{ji} to the j^{th} cross-section **16** at the location of the ij^{th} cross-hair **18**. More particularly, the surface normal vector n_{ij} (of the underlying object) at the location of the ij^{th} cross-hair **18** is orthogonal to both t_{ij} and t_{ji}. If the i^{th} cross-section is a local geodesic, then n_{ij} is also orthogonal to the cross-section normal n_i. However, there can only be three mutually orthogonal vectors in R^3. Accordingly, the cross-section normal n_i must be co-linear with t_{ji}.

If both the i^{th} cross-section **16** and the j^{th} cross-section **16** at a cross-hair **18** are local geodesics, then this orthogonality property can be expressed as:

$$t_{ij} \times n_j = 0 \text{ and } t_{ji} \times n_i = 0 \tag{3}$$

It is not always the case that both cross-sections **16** at a cross-hair **18** are local geodesics. It may be demonstrated that where γ=γ=0, the block **204** characterization requires that at least one cross-section **16** at a cross-hair **18** be a local geodesic, but there are circumstances where the other one of the cross-sections **16** at a cross-hair **18** is not a local geodesic. Accordingly, the equation (3) observation is one that may be true for some, but not necessarily all cross-hairs **18**. This can make the equation (3) observation suitable for use in an objective function of an optimization problem.

In some embodiments, another observation used in the block **206** is that designers/artists tend to use informative viewpoints which minimize or reduce foreshortening over the entire drawing. A single cross-hair **18** between an i^{th} cross-section **16** and a j^{th} cross-section **16** is minimally foreshortened where both the tangent to i^{th} cross-section **16** at the location of the cross-hair **18** (t_{ij}) and the tangent to the j^{th} cross-section **16** at the location of the cross-hair **18** (t_{ji}) are in the view plane. If a three-dimensional coordinate system is constructed such that the z-axis or z-direction is orthogonal to the view frame, an expression representative of the foreshortening over all of the cross-hairs **18** in the concept drawing is given by:

$$\Sigma[(t_{ij}^{z})^2+(t_{ji}^{z})^2] \tag{4}$$

where the sum is taken over all of the cross-hairs **18** in the concept drawing and t_{ij}^{z} and t_{ji}^{z} are the z-components of the tangent vectors t_{ij} and t_{ji} of the two cross-sections **16** at the location of each cross-hair **18**. The minimal foreshortening observation is then satisfied when the equation (4) sum is minimized. As was the case with the observation of equation (3), it is not always the case that foreshortening is absolutely minimized over an entire concept drawing. Accordingly, the equation (4) observation can be suitable for use in an objective function of an optimization problem.

Block **206** involves setting up an optimization problem which may be used to solve for some of the three-dimensional characteristics of the block **202** input concept drawing. In some embodiments, these three-dimensional characteristics can include information that defines (in a three-dimensional coordinate system) one plane for each cross-section **16** in the concept drawing, where each cross-section **16** lies on its corresponding plane. In some embodiments, these three-dimensional characteristics may also include information desirable to obtain three-dimensional representations (i.e. representations in the three-dimensional coordinate system) of the tangent vectors to the cross-sections **16** at the locations of the cross-hairs **18** in the concept drawing. It is assumed, for the purposes of this description that the x and y-axes of the three-dimensional coordinate system are the axes of the view plane and that the z-axis is the axis orthogonal to the view plane and in the view direction, where the positive z-direction is toward the viewer and the negative z-direction is away from the viewer. Accordingly, the x and y-axes of the tangent vectors to the cross-sections at the locations of the cross-hairs **18** in the concept drawings may be known and the block **206** optimization set up may be used to solve for the z-components of these tangent vectors.

A constrained optimization problem involves minimizing an objective function subject to one or more constraints. Accordingly, block **206** may involve configuring an objective function and/or one or more constraints. In some embodiments, the objective function and/or constraints may be preconfigured.

In some particular embodiments, the output of the constrained optimization comprises a set of parameters which define (in a three-dimensional coordinate system) one plane for each cross-sections **16** in the concept drawing, where each cross-section **16** lies on its corresponding plane. As is known, a plane can be described in a three-dimensional coordinate system by a normal vector n and an offset value c, where the normal vector n represents the orientation of the plane and c represents the location of the plane in the three-dimensional coordinate system (e.g. c may represent a closest distance from the origin of the three-dimensional coordinate system to the plane). The plane can then be described according to the plane equation:

$$x \cdot n + c = 0 \tag{5}$$

where x is the position vector extending from the origin to a location (x,y,z) on the plane. Thus, in some embodiments, the optimization problem set up in block **206** comprises an optimization problem which determines the parameters n_i (i.e. the cross-section normal for the plane corresponding to the i^{th} cross-section **16**) and c_i (i.e. the offset value for the plane corresponding to the i^{th} cross-section **16**) for each of the cross-sections **16** in the concept drawing.

In some particular embodiments, the output of the constrained optimization comprises a set of parameters which define (in the three-dimensional coordinate system) t_{ij}^{z} and t_{ji}^{z} (i.e. the z-components of the tangent vectors t_{ij} and t_{ji} to the i^{th} and j^{th} cross-sections **16** at the location of cross-hair **18** corresponding to their intersection) for each of the cross-hairs **18** in the concept drawing. It will be appreciated that the x and y-components of the tangent vectors t_{ij} and t_{ji} may be known from the concept drawing input in block **202** or and/or from block **202** analysis discussed above.

In some particular embodiments, the objective function for the block **206** optimization problem set up is based at least in part on the observation of equation (3) (or the magnitudes of the equation (3) expressions) for each of the cross-hairs **18** in the concept drawing. In some particular embodiments, the objective function for the block **206** optimization problem set up is based at least in part on the observation of equation (4) over the cross-hairs **18** in the concept drawing. In some particular embodiments, the objective function of the block **206** optimization problem set up is based at least in part on both the magnitude of the equation (3) expressions and the observation of equation (4) over the cross-hairs in the concept drawing. For example, in such embodiments, the block **206** objective function comprises:

$$\text{obj.function}=f(|t_{ij}\times n_j|,|t_{ji}\times n_i|,(t_{ij}^{z})^2+(t_{ji}^{z})^2) \tag{6}$$

evaluated at each cross-hair **18** in the concept drawing. In some embodiments, the parameters $|t_{ij}\times n_j|$ and $|t_{ji}\times n_i|$ may be replaced by $|t_{ij}\times n_j|^2$ and $|t_{ji}\times n_i|^2$, where $|t_{ij}\times n_j|^2$ and $|t_{ji}\times n_i|^2$ represent different evaluations of the magnitude of the equation (3) expressions and which may reduce the need to compute square roots and the corresponding computational expense.

In some particular embodiments, the objective function of the block **206** optimization problem set up is based on a linear combination of the parameters $|t_{ij}\times n_j|$, $|t_{ji}\times n_i|$, $(t_{ij}^{z})^2+(t_{ji}^{z})^2$ evaluated at each cross-hair **18** in the concept drawing or on a linear combination of the parameters $|t_{ij}\times n_j|^2$, $|t_{ji}\times n_i|^2$, $(t_{ij}^{z})^2+(t_{ji}^{z})^2$ evaluated at each cross-hair **18** in the concept drawing. In some embodiments, such a linear combination can be expressed as:

$$\text{obj.function}=\Sigma_{ij}(a_{ij}|t_{ij}\times n_j|^2+b_{ij}|t_{ji}\times n_i|^2+d_{ij}[(t_{ij}^{z})^2+(t_{ji}^{z})^2]) \tag{7}$$

where the sum over ij represents the sum over each cross-hair **18** in the concept drawing and a_{ij}, b_{ij}, d_{ij} represent configurable weighting coefficients. In some particular non-limiting embodiments, the inventors have achieved desirable results by setting $a_{ij}=b_{ij}=d_{ij}=1$ for all ij.

While a number of exemplary objective functions are described herein, it will be appreciated that other objective functions could be constructed which may be based at least in part on the observation of equation (3) (or the magnitudes of the equation (3) expressions) for each of the cross-hairs **18** in the concept drawing and/or on the observation of equation (4) over all of the cross-hairs **18** in the concept drawing. Embodiments of the invention should be understood to include any such objective functions.

In some particular embodiments, the constraints for the block **206** optimization problem set up are based at least in part on the block **204** characterization of the concept drawing.

For example, in some embodiments the constraints for the block **206** optimization problem set up comprise:

$$|n_i \cdot n_j| \le \epsilon \text{ or } -\epsilon \le n_i \cdot n_j \le \epsilon \text{ for all } ij \quad (1)$$

where ϵ is a positive number close to zero and is a parameter which may be configurable and which may be used to accommodate error in the concept drawing. In some embodiments the constraints for the block **206** optimization problem set up additionally or alternatively comprise:

$$|t_{ij} \cdot t_{ji}| \le \gamma \text{ or } -\gamma \le t_{ij} \cdot t_{ji} \le \gamma \text{ for all } ij \quad (2)$$

where γ is a positive number close to zero and is a parameter which may be configurable and which may be used to accommodate error in the concept drawing. The parameters ϵ and γ may be user-configurable depending on the confidence in the accuracy of the input concept drawings. In some embodiments, where the confidence in the accuracy of the input concept drawings is relatively low, the parameters ϵ and γ may be set to be in a range of 0.075-0.15. In some embodiments, where the confidence in the accuracy of the input concept drawings is relatively high, the parameters ϵ and γ may be set to be in a range of 0.025-0.075.

In some embodiments the constraints for the block **206** optimization problem set up additionally or alternatively comprise one or more geometric relationships, such as:

$$t_{ij} \cdot n_i = 0 \text{ for all } ij \quad (8a)$$

and

$$t_{ji} \cdot n_j = 0 \text{ for all } ij \quad (8b)$$

These constraints arise directly out of the geometry. For example, the i^{th} plane includes the i^{th} cross-section **16** and therefore includes the tangent vector t_{ij} at the location of the cross-hair **18** where the i^{th} cross-section **16** intersects the j^{th} cross-section **16** and the cross-section normal II; is orthogonal to the i^{th} plane by definition.

In some embodiments, the block **206** optimization problem set up may involve making one or more assumptions that can reduce the computing resources required to perform the block **208** optimization. For example, normal vectors to planes (e.g. cross-section normal vectors n_i) are typically defined to have unit length. However, the inventors have found that it is more convenient in some circumstances to set the z-component (i.e. the view direction component) of the cross-section normal vectors n_i to be of unit length (i.e. $n_i^z=1$) for all i. This assumption may reduce the complexity (e.g. the polynomial order) of one or more of the expressions in some block **206** optimization problem formulations or one or more terms in any such expressions. This assumption (i.e. setting $n_i^z=1$ for all i) works effectively where the planes which include cross-sections **16** of concept drawings are not orthogonal to the view plane (i.e. where the cross-sections **16** are not straight lines in the concept drawing).

In some embodiments, the block **206** optimization problem set up may take advantage of the fact that at the location of each cross-hair **18** in the three dimensional coordinate system, the three-dimensional representations of the cross-section curves **16** share the same z-component. Using this observation, the block **206** optimization problem set up may define an offset value c for each plane containing a cross-section **16** in the concept drawing, where the offset value c_i represents a location of the i^{th} plane in the three-dimensional coordinate system (e.g. c_i may represent a closest distance from the origin of the three-dimensional coordinate system to the i^{th} plane). Accordingly, for the ij^{th} cross-hair **18** at a location $x=\langle x_x, x_y, x_z\rangle$ in the three-dimensional coordinate system, the i^{th} and j^{th} planes at the cross-hair **18** may be defined by the plane equations:

$$x \cdot n_i + c_i = 0 \quad (9a)$$

and

$$x \cdot n_j + c_j = 0 \quad (9b)$$

From the earlier block **206** assumption discussed above, $n_i^z=n_j^z=1$. Accordingly, equation (9b) can be subtracted from equation (9a) to yield:

$$x_x(n_i^x - n_j^x) + x_y(n_i^y - n_j^y) + (c_i - c_j) = 0 \quad (10)$$

For each ij^{th} cross-hair **18**, equation (10) expresses the offset values c_i, c_j of the corresponding i^{th} and j^{th} planes in terms of the x and y locations of the cross-hair **18** (which are known) and the cross-section normal vectors n_i, n_j. Accordingly, in some embodiments, equation (10) may be used as an additional constraint in the block **206** optimization problem set up. In some embodiments, equation (10) may be substituted into any of the objective function and/or the constraints of the block **206** optimization problem (e.g. to reduce the computational expense associated with the optimization problem). In some embodiments, block **206** may involve selecting one arbitrarily chosen cross-hair **18** to be the origin of the three-dimensional coordinate system (i.e. to have a location $x=\langle x_x, x_y, x_z\rangle=\langle 0,0,0\rangle$ and the two corresponding planes to have offset values $c_i=c_j=0$.

Once the optimization problem has been set up in block **206**, method proceeds to block **208** where the optimization is performed. In some embodiments, the block **208** optimization is performed using an interior point optimization algorithm. This is not generally necessary. Some embodiments may make use of additional or alternative optimization algorithms which are known or may become known to those skilled in the art. Suitable constrained optimization algorithms that may be used in block **208** include, without limitation, a variety of non-linear modern optimization techniques.

The block **208** optimization determines the cross-section normal vectors m in a three-dimensional coordinate system for each cross-section **16** in the input concept drawing, where n_i represents the cross-section normal vector for the i^{th} plane which includes the i^{th} cross-section **16**. The block **208** optimization may also obtain the offset values c_i in the three dimensional coordinate system for each cross-section **16** in the input concept drawing, where c_i represents the offset value for the i^{th} plane which includes the i^{th} cross-section **16** (e.g. c_i may represent a closest distance from the origin of the three-dimensional coordinate system to the i^{th} plane). The block **208** optimization may also comprise determining a set of parameters which define (in the three-dimensional coordinate system) t_{ij}^z and t_{ji}^z (i.e. the z-components of the tangent vectors t_{ij} and t_{ji} to the i^{th} and j^{th} cross-sections **16** at the location of the cross-hair **18** corresponding to their intersection) for each of the cross-hairs **18** in the concept drawing. It will be appreciated that the x and y-components of the tangent vectors t_{ij} and t_{ji} may be known from the concept drawing input in block **202** or and/or from block **204** analysis discussed above. Further, it will be appreciated that t_{ij}^z and t_{ji}^z can be computed from knowledge of the cross-section normal vectors n_i at each cross-hair **18**. These outputs of the block **208** optimization process are shown in FIG. **2**B as optimization outputs **270**.

The block **208** optimization may involve determining an initial guess for the optimization process. In some embodiments, this initial guess may be performed as part of the block

206 optimization set up. This initial guess may be used to help ensure that the block 208 optimization yields a consistent set of cross-hair orientations. In some embodiments, this initial guess may comprise a set of solutions (e.g. n_i, c_i and t_{ij}^z and t_{ji}^z) for an initial pair of cross-hairs 18 and this information may specify the orientation at the initial pair of cross-hairs 18 to thereby remove the orientation ambiguity discussed above. In some embodiments, it is sufficient to specify a subset of the data for the initial pair of cross-hairs 18 as this initial guess. For example, it is not necessary in some embodiments to specify the offsets c_i. Further, if n_i is known, then t_{ij}^z and t_{ji}^z may be determined from n_i and vice versa. Consequently, in some embodiments, the initial guess at the initial pair of cross-hairs may comprise n_i or t_{ij}^z and t_{ji}^z. In some embodiments, the initial guess at the initial pair of cross-hairs may comprise c_i and one of: n_i or t_{ij}^z and t_{ji}^z. For each of the initial pair of cross-hairs 18, determining the initial guess may involve: analytically minimizing foreshortening at the initial cross-hair 18 (e.g. analytically minimizing $(t_{ij}^z)^2+(t_{ji}^z)^2$ for the initial cross-hair 18 by setting this expression to be equal to zero), while strictly enforcing the other properties (e.g. requiring that for the initial cross-hair 18: $n_i \cdot n_j=0$; $t_{ij} \cdot t_{ji}=0$; $t_{ij} \times n_j=0$; and $t_{ji} \times n_i=0$) and assuming that the initial cross-hair is independent of any other cross-hairs (e.g. that values are zero for all other cross-hairs). Such analytic solutions are obtained for a pair of initial cross-hairs 18.

It will be appreciated that the above-described technique for determining the initial guesses at the initial cross-hairs 18 may yield two solutions (where the surface normal faces the viewer) for each initial cross-hair 18, since there is orientational ambiguity associated with the initial cross-hairs 18 as discussed above. In circumstances where a cross-section 16 intersects a silhouette 12, this orientational ambiguity may be removed by selecting initial cross-hairs 18 which are closest to the intersection of the cross-section 16 and the silhouette 12 and selecting (as initial guesses) the solutions which are consistent with the orientation of the tangent t_s in the immediate vicinity of the silhouette 12, as described above (see FIG. 3F and block 116 characterization property (FIG. 3A)).

In circumstances where there is no intersection between a silhouette 12 and a cross-section 16, then the two initial cross-hairs 18 may be selected to be far apart from one another. Since there will be two solutions for each of the initial cross-hairs 18 and there are two initial cross-hairs 18, there will be a total of four combinations of initial guesses. In such cases, block 208 may comprise performing the optimization for all four combinations of initial guesses and then selecting the solution that is most consistent with typical viewer perceptions. Typically, viewer perceptions have been studied and it has been found that, on average, viewers prefer interpretations consistent with viewing objects from above and/or with convex shapes (as opposed to concave shapes). Additionally or alternatively, user-selection may be solicited to enforce an orientation. Such user selection may involve selecting one or more of the orientation(s) of the initial guesses at the initial cross-hairs 18 and/or selecting between the solutions generated by the four combinations of initial guesses.

At the conclusion of the block 208 optimization process, the illustrated embodiment of method 200 has determined: the cross-section normal vectors n_i in a three-dimensional coordinate system for each cross-section 16 in the input concept drawing, where n_i represents the cross-section normal vector for the i^{th} plane which includes the i^{th} cross-section 16; the offset values c_i in the three dimensional coordinate system for each cross-section 16 in the input concept drawing, where c_i represents the offset value for the i^{th} plane which includes the i^{th} cross-section 16; and t_{ij}^z and t_{ji}^z (i.e. the z-components of the tangent vectors t_{ij} and t_{ji} to the i^{th} and j^{th} cross-sections 16 at the location of the cross-hair 18 corresponding to their intersection) for each of the cross-hairs 18 in the concept drawing. It will be appreciated that the x and y-components of the tangent vectors t_{ij} and t_{ji} (i.e. t_{ij}^x and t_{ji}^x and t_{ij}^y and t_{ji}^y) may be known from the concept drawing input in block 202 or and/or from block 204 analysis discussed above. Further, it will be appreciated that t_{ij}^z and t_{ji}^z can be computed from knowledge of the cross-section normal vectors n_i at each cross-hair 18. These outputs of the block 208 optimization process are shown in FIG. 2B as optimization outputs 270.

Method 200 then proceeds to block 210 which involves generating a normal vector field comprising a plurality of cross-hair surface normal vectors in the three-dimensional coordinate system. Each cross-hair surface normal vector n_{ij} generated in block 210 is located at the location, in the three-dimensional coordinate system, of the ij^{th} cross-hair where the i^{th} one of the cross-sections intersects the j^{th} one of the cross-sections and is estimated to be oriented orthogonally to the surface of the object underlying the concept drawing at the location of the ij^{th} cross-hair. Generating the cross-hair surface normal vectors may be based at least in part on one or more of: the plurality of cross-section normal vectors (e.g. n_i), the plurality of tangent vectors (e.g. t_{ij} and t_{ji}) and the plurality of offset values c_i. In some embodiments, for each cross-hair 18, the cross-hair surface normal vector n_{ij} at the location of the ij^{th} cross-hair 18 can be determined in block 210 from the tangent vectors t_{ij} and t_{ji} at the location of the ij^{th} cross-hair 18 according to:

$$n_{ij}=t_{ij}\times t_{ji} \tag{11}$$

The output 280 of block 210 is a field of surface normal vectors n_{ij} at the locations of cross-hairs 18 in the three-dimensional coordinate system and estimated to be orthogonal to the surface of the object underlying the concept drawing. These output surface normal vectors n_{ij} at the locations of cross-hairs 18 are shown in FIG. 2C as output 280.

Once the surface normal vectors n_{ij} are determined at the locations of cross-hairs 18 in block 210, then method 200 may optionally involve propagating the cross-hair surface normal vectors to locations away from cross-hairs 18 (e.g. to further populate the normal vector field at locations away from cross-hairs 18). It can be desirable to further populate the normal vector field at locations away from cross-hairs 18 to provide further indicators of three-dimensional information corresponding to the object underlying the concept drawing.

In the illustrated embodiment, the surface normal vectors n_{ij} at the locations of cross-hairs 18 may first be propagated along cross-sections 16 in block 212. A graphical illustration of this block 212 process is shown process is shown in FIG. 4. FIG. 4 shows three cross-sections 16*a*, 16*b* and 16*c* with two cross-hairs 18*ab*, 18*ac*, where cross-hair 18*ab* represents the cross-hair between cross-sections 16*a*, 16*b* and cross-hair 18*ac* represents the cross-hair between cross-sections 16*a*, 16*c*. FIG. 4 also shows a location x on cross-section 16*a* that is located between cross-hairs 18*ab*, 18*ac*. FIG. 4 shows the following vectors at the location of cross-hair 18*ab*:

t_{ab} which is the tangent along cross-section 16*a*;

t_{ba} which is the tangent along cross-section 16*b*; and

$n_{ab}=t_{ab}\times t_{ba}$ which is the cross-hair surface normal vector.

These vectors at cross-hair 18*ab* are known from the preceding blocks of method 200. FIG. 4 also shows the following vectors at the location of cross-hair 18*ac*:

t_{ac} which is the tangent along cross-section 16*a*;

t_{ca} which is the tangent along cross-section 16*c*; and

$n_{ac}=t_{ac}\times t_{ca}$ which is the cross-hair surface normal vector.

Again, these vectors at cross-hair **18***ac* are known from the preceding blocks of method **200**.

The surface normal vector propagation of block **212** may involve determining the following vectors at the location x between cross-hairs **18***ab*, **18***ac* on cross-section **16***a:*

- t_{ax} which is the tangent along cross-section **16***a;*
- t_{xa} which is estimated to be another tangent to the surface of the object underlying the concept drawing; and
- n_{ax} which is estimated to be a surface normal vector on the surface of the object underlying the concept drawing.

The tangent vector t_{ax} is known or determinable from the knowledge of the two-dimensional cross-section **16***a* and from the three-dimensional knowledge of the a^{th} plane which includes the cross-section **16***a*. In some embodiments, the vector t_{xa} is determined in block **212** according to an arc-length based weighted average of t_{ba} and t_{ca}. In one particular embodiment, the vector t_{xa} is determined in block **212** according to:

$$t_{xa} = \frac{\sigma t_{ba} + \psi t_{ca}}{\Psi + \sigma} \tag{12}$$

where Ψ is an arc length along cross-section **16***a* between cross-hair **18***ab* and point x and σ is an arc length along cross-section **16***a* between cross-hair **18***ac* and point x. In some embodiments, the arc length is normalized, such that $\Psi+\sigma=1$, in which case equation (12) can be reduced to $t_{xa}=\sigma t_{ba}+(1-\sigma)t_{ca}$. Once t_{xa} is determined, then the surface normal vector n_{ax} can be determined according to $n_{ax}=t_{ax}\times t_{xa}$.

It will be appreciated that the location x is an arbitrary location on a cross-section **16***a* between two cross-hairs **18***ab*, **18***ac* and so block **212** may involve determining surface normal vectors at a plurality of locations x along cross-section **16***a*. For example, block **212** may determine surface normal vectors at any suitable spacing (e.g. any suitable arc length spacing) along cross-section **16***a* as may be desired or required for a particular application. Also, it will be appreciated that cross-section **16***a* and cross-hairs **18***ab*, **18***ac* are arbitrary and so block **212** may involve determining surface normal vectors on any or all of the cross-sections **16** in a concept drawing at any locations between pairs of cross-hairs **18**.

Block **212** may also involve determining surface normal vectors at locations along a cross-section **16** that are not between cross-hairs **18**. This situation is shown in FIG. **4** at a location y which is also on cross-section **16***a*, but is not between cross-hairs **18**. In this situation, the vectors at the nearest cross-hair **18***ac* can be used to determine the surface normal vector n_{ay} at location y by determining $n_{ay}=t_{ay}\times t_{ya}$, where t_{ay} is known or determinable from the knowledge of the two-dimensional cross-section **16***a* and from the three-dimensional knowledge of the a^{th} plane which includes the cross-section **16***a* and where t_{ya} at location y is assumed to be the same as t_{ca} at the location of the nearest cross-hair **18***ac*. Again, it will be appreciated that the location y as well as the cross-section **16***a* and cross-hair **18***ac* are arbitrary, so block **212** may use this technique to determine surface normal vectors for any locations which are not between pairs of cross-hairs **18** on any or all of the cross-sections **16** in a concept drawing.

The output **285** of block **212** is a field of surface normal vectors in the three-dimensional coordinate system at a plurality of locations along the cross-sections **16** of the concept drawing (shown in FIG. **2**B as surface normal vectors **285**), where the surface normal vectors are estimated to be orthogonal to the surface of the object underlying the concept drawing.

Method **200** may then proceed to optional block **214** which involves further populating the surface normal vector field by determining surface normal vectors in locations between cross-sections **16** or otherwise not on cross-sections **16**. FIG. **5**A illustrates a block diagram of a method **500** for determining surface normal vectors in locations between cross-sections **16** or otherwise not on cross-sections **16** of concept drawing **10** which may be used to implement block **214** according to a particular embodiment. In accordance with method **500**, the locations for which surface normal vectors are determined are the two-dimensional locations on the view plane (e.g. the x-y plane using the notation of this description), although the surface normal vectors themselves are three-dimensional vectors in the three-dimensional coordinate system. The locations of known surface normal vectors at locations in the three-dimensional coordinate system (e.g. surface normal vectors at cross-hairs and along cross-sections) can be projected back to the view plane by removing their depth (e.g. z coordinate).

The particular embodiment shown in method **500** involves the application of the so-called Coons interpolation technique using discrete bi-linearly blended Coons patches as described by Farin, G. and Hansford, D. 1999. Discrete Coons Patches. *Computer Aided Geometric Design* 16 (August), 691-700, which is hereby incorporated herein by reference. This Coons patches technique is used on a region bounded by four curves, where a discrete set of normal vectors are defined at discrete locations along each curve. To apply this Coons patches technique, method **500** first involves processing the information known from the rest of method **200** to obtain suitable regions for the application the Coons patches technique.

Method **500** starts in block **502** which involves extending "hanging" cross-sections **16** until they intersect a boundary curve (e.g. a silhouette **12** or a sharp boundary **14**—see FIG. **1**). A hanging cross-section **16** is a cross-section that terminates at a location other than on a boundary curve. In one particular embodiment, extending a hanging cross-section **16** in block **502** involves extending the hanging cross-section **16** to the nearest silhouette **12** or sharp boundary **14**, where such extending is in the direction of the tangent vector to that cross-section **16** at its terminus. As discussed above, the tangent vectors to cross-sections **16** are known or determinable at all locations on cross-sections **16**. Method **500** then proceeds to block **504** which involves determining a plurality of regions that are bounded by curves (either by cross-sections **16** or cross-sections **16** in combination with boundary curves (i.e. silhouettes **12** or sharp boundaries **14**). Such regions can be extracted, for example, by creating a planar map of the curves.

Method **500** then proceeds to block **506** which involves further processing the block **506** regions, if necessary, to set up the region for application of the discrete Coons patches interpolation. Block **506** may involve classifying the block **504** regions into one of a number of classification types and then processing each region in accordance with its classification type to provide a region having characteristics suitable for application of the discrete Coons patches interpolation. The block **506** classification may involve an analysis of the types of curves that bound the region. In one particular embodiment, the block **506** may include the following classification types:

- Type I: regions bounded by four cross-sections **16**;
- Type II: regions bounded by a number n of cross-sections **16**, where $n\neq 4$;

Type III: regions bounded by more than 3 consecutive cross-sections **16** and by a boundary curve (e.g. a silhouette **12** or a sharp boundary **14**);

Type IV: regions bounded by 2 or 3 consecutive cross-sections **16** and by boundary curves.

The regions in type I are bounded by four cross-sections **16** on which surface normal vectors are known (by the earlier operations of method **200**). Consequently, type I regions are suitable for the application of Coons patches interpolation without further processing in block **506**. In accordance with method **500** of the FIG. **5**A embodiment, Coons patches interpolation is applied to the type I regions in block **508** to propagate surface normal vectors to the interior of the type I regions.

The regions of type II are bounded by a number n of cross-sections **16** on which surface normal vectors are known, where n≠4. In one particular embodiment, type II regions are processed in block **506** to apply a midpoint subdivision of the type II region to generate n four-"sided" sub-regions. This process is schematically depicted in FIG. **5**B, where a three-sided type II region **520** is subdivided into three four-sided sub-regions **522**A, **522**B, **522**C. The location of the midpoint **524** of the inserted sub-region boundaries **526** may be selected in accordance with templates of the type described by Nasri A. et al. 2009. Filling N-Sided Regions by Quad Meshes for Subdivision Surfaces. *Computer Graphics Forum* 28, 6 (September), 1644-1658 which is hereby incorporated herein by reference. Surface normal vectors may be assigned to the inserted sub-region boundaries **526** using the discrete Coons formulation described by Farin, G. and Hansford, D. 1999, treating adjacent sub-regions **522** as a single four-sided region. Once surface normal vectors are defined on the inserted sub-region boundaries **526**, then each sub-region **522** can be processed by application of Coons patches interpolation (in block **508**) to propagate surface normal vectors to the interior of sub-region **522**.

The regions of type III are bounded by more than 3 consecutive cross-sections **16** and by a boundary curve (e.g. a silhouette **12** or a sharp boundary **14**). In their initial form, type III regions are unsuitable for the application of Coons patches interpolation because there are no surface normal vectors defined on the boundary curve. In one particular embodiment, the type III regions are processed in block **506** to estimate surface normal vectors on the boundary curve by copying normal vectors from one or more opposing (i.e. non-adjacent) cross-sections **16** onto the boundary curve and then rotating the copied normal vectors on the boundary curve to agree with the normal vectors of adjacent cross-sections **16** at the extremities of the boundary curve. This process is shown schematically in FIG. **5**C, where a type III region is bounded by four consecutive cross-sections **16** on which surface normal vectors are known and includes a boundary curve (e.g. a sharp boundary **14**) which initially has no surface normal vectors. The middle illustration of FIG. **5**C shows how normal vectors from the opposing cross-sections are copied onto sharp boundary **14**. Then, the rightmost illustration of FIG. **5**C shows how the normal vectors copied onto sharp boundary **14** are rotated, to agree with the normal vectors of the adjacent cross-sections **16** at the extremities of sharp boundary **14**. Normal vectors on the interior of the sharp boundary **14** (i.e. between the extremities of sharp boundary **14**), may be rotated based on an arc-length weighted average between the rotations at the extremities of sharp boundary **14**. This process can also be used where the boundary curve is a silhouette **12**. However, where the boundary curve of a type III region is a silhouette **12**, another embodiment for determining the normal vectors on the silhouette **12** comprises computing normal vectors from the normal vectors to the two-dimensional curve of the silhouette **12**, since, for silhouettes **12**, their two-dimensional normal vectors correspond to the normal vectors in the three-dimensional coordinate system.

Since the initial type III region has more than three (i.e. four or more) consecutive cross-sections **16**, once the normal vectors are defined on the boundary curve, the type III region will be bounded by more than four curves on which normal vectors are defined. Thus, the type III region may be further processed in a manner similar to that discussed above for the type II region to reduce the type III region to a plurality of four-sided sub-regions. Once divided into four-sided sub-regions, these four-sided sub-regions can be processed by application of Coons patches interpolation (in block **508**) to propagate surface normal vectors to the interior of the sub-regions.

The regions of type IV are bounded by 2 or 3 consecutive cross-sections **16** and by one or more boundary curves (e.g. silhouettes **12** or sharp boundaries **14**). In their initial form, type IV regions are unsuitable for the application of Coons patches interpolation because there are no surface normal vectors defined on the boundary curve. In one particular embodiment, the type IV regions are processed in block **506** to generate an expanded four-sided region that overlaps the boundary curve and to define surface normal vectors on the newly created boundaries of the expanded four-sided region. Coons patches interpolation may then be applied to the expanded four-sided region in block **508**. The expanded four-side region may then be post processed in block **510** (FIG. **5**A) to remove the extraneous parts—i.e. the parts of the expanded region outside of the original type IV region. This process is shown schematically in FIG. **5**D, where a type IV region **540** is bounded by two consecutive cross-sections **16** on which surface normal vectors are known and includes a boundary curve (e.g. a silhouette **12**) which initially has no surface normal vectors. In the illustrated FIG. **5**D embodiment, an expanded four-sided region **542** is created by: extending cross-sections **16** along at their extremities along directions indicated by their known tangents at their extremities to produce extended cross-sections **16'**; creating the four-sided expanded region **542** by creating synthetic curves **16"** at the extremities of the their adjacent extended cross-sections **16'** and having curvatures similar to their opposing extended cross-sections **16'**; and then estimating normal vectors along synthetic curves **16"** by: copying the normal vectors from the known (non-adjacent) cross-section curves **16** onto the synthetic curves **16"**, rotating the normal vectors at the extremities of the synthetic curves **16"** to make the normal vectors at the extremities of synthetic curves **16"** agree with the normal vectors of extended cross-sections **16'** and performing an arc-length weighted average rotation on the normal vectors between the extremities of synthetic curves **16"**. Once the surface normal vectors are known on the four-sided expanded region **542**, then Coons patches interpolation may then be applied to the expanded four-sided region in block **508**. The expanded four-side region may then be post processed in block **510** (FIG. **5**A) to remove the extraneous parts—i.e. the parts of the expanded region **542** outside of the original type W region **540**. The remaining interpolated surface normal vectors in the original type IV region **540** may then provide the surface normal vectors representing the output of method **500** (block **214**).

Returning to FIG. **2**B, the output **290** of block **214** is a field of three-dimensional surface normal vectors that are defined at suitably quantized locations on the view plane and within the boundary curves (silhouettes **12** or sharp boundaries **14**) of the concept drawing. These surface normal vectors as shown in FIG. 2B as output surface normal vectors **290**. The specific surface normal vectors generated in block **214** are located away from the cross-sections. The surface normal vectors **290** are estimated to be orthogonal to the surface of the object underlying the concept drawing.

Method **200** may proceed to optional block **216** which may involve using further processing based on any of: output **270** of block **208** (e.g. cross-section normal vectors and offsets which define the three-dimensional planes that include cross-sections **16** and the three-dimensional tangent vectors at the cross-hairs **18**), output **280** of block **210** (e.g. surface normal vectors at the locations of cross-hairs **18**), output **285** of block **212** (e.g. surface normal vectors at suitably quantized locations along cross-sections **16**) and/or output **290** of block **214** (e.g. surface normal vectors at locations other than on cross-sections **16**). The further processing in optional block **216** may produce its own output **295** as shown in FIG. 2B. By way of non-limiting example, such optional block **216** further processing may involve application of shading to the concept drawing based on the surface normal vector field output **280**, **285**, **290** from blocks **210**, **212** and/or **214**. Techniques for generating such shading based on surface normal vector fields (e.g. Phong shading and/or the like) are known in the art. Other non-limiting examples of further processing that could be performed in optional block **216** include: constructing a partial three-dimensional model of the object underlying the block **202** input concept drawing **10**; three-dimensional layering of two-dimensional concept drawings onto one another to respect surface depth and orientation; generating stereoscopic images of the object underlying the block **202** input concept drawing **10**; three-dimensional presentation renderings of the object underlying the block **202** input concept drawing **10**; combining the outputs of multiple iterations of method **200**; and/or the like.

One aspect of the invention provides a method for generating shading to provide three-dimensional appearance to an object underlying a concept drawing. FIG. 2C is a block diagram of a method **300** for generating a normal vector field that represents a surface of an object underlying a concept drawing and generating representative shading for the object underlying the concept drawing based on the surface normal vector field according to a particular embodiment. Method **300** is implemented, at least in part, by one or more computers or suitably configured processors **350**—shown in dashed lines in FIG. 2C. Method **300** starts in block **302** which involve procuring a concept drawing **10**. Block **302** may be substantially similar to blocks **102**, **202** described above. Method **300** then proceeds to block **304** which involves determining estimates of the surface normal vectors **320** of the object underlying the block **302** concept drawing. These surface normal vectors **320** may be determined in block **304** in accordance with method **200** (e.g. blocks **204-214**) described above. Method **300** then proceeds to block **306** which involves generating shading information **330** for concept drawing **10** using the block **304** surface normal vectors **320**. Techniques for generating such shading based on surface normal vector fields (e.g. Phong shading and/or the like) are known in the art.

Another aspect of the invention provides a method for characterizing an object underlying a concept drawing, the concept drawing comprising a plurality of cross-sections and a plurality of cross-hairs, each cross-hair comprising an intersection of two corresponding cross-sections. The characterization method comprises determining parameters for a plurality of planes in a three-dimensional coordinate system, each of the planes including a corresponding one of the cross-sections. The characterization method may optionally involve determining an estimate of the curves of the cross-sections in the three-dimensional coordinate system wherein the curve for each cross-section in the three-dimensional coordinate system is located on the plane corresponding to the cross-section. The characterization method is implemented, at least in part, by one or more computers or suitably configured processors. The method comprises performing a constrained optimization which minimizes an objective function subject to one or more constraints to solve for: a plurality of cross-section normal vectors, each cross-section normal vector n_i corresponding to an i^{th} one of the cross-sections and normal to an i^{th} plane defined in a three-dimensional coordinate system and such that the i^{th} plane includes the i^{th} one of the cross-sections; a plurality of tangent vectors in the three-dimensional coordinate system, each tangent vector t_{ij} corresponding to an ij^{th} one of the cross-hairs and comprising a tangent to the i^{th} one of the cross-sections at a location, in the three-dimensional coordinate system, of the ij^{th} cross-hair where the i^{th} one of the cross-sections intersects the j^{th} one of the cross-sections; and a plurality of offset values, each offset value c_i representing a location of the i^{th} plane in the three-dimensional coordinate system (e.g. c_i may represent a closest distance from the origin of the three-dimensional coordinate system to the i^{th} plane). One particular embodiment of this aspect of the invention may be implemented by performing the procedures of blocks **202-210** of method **200** described above to generate output **270** described above or a subset of output **270** described above.

Certain implementations of the invention comprise systems comprising one or more computers or suitably configured processors which execute software instructions which cause the processors to perform at least part of one or more methods of the invention. For example, a system may comprise one or more computers or suitably configured processors that implement methods as described herein (or parts thereof) by executing software instructions from a program memory accessible to the computers and/or processors. The invention may also be provided in the form of a program product. The program product may comprise any medium which carries a set of computer-readable data comprising instructions which, when executed by a data processor, cause the data processor to execute a method of the invention. Program products according to the invention may be in any of a wide variety of forms. The program product may comprise, for example, physical media such as solid state memory, magnetic data storage media including floppy diskettes, hard disk drives, optical data storage media including CD ROMs, DVDs, electronic data storage media including ROMs, flash RAM, or the like. The computer-readable data on the program product may optionally be compressed or encrypted.

Where a component (e.g. a controller, computer, processor, etc.) is referred to above, unless otherwise indicated, reference to that component (including a reference to a "means") should be interpreted as including as equivalents of that component any component which performs the function of the described component (i.e., that is functionally equivalent), including components which are not structurally equivalent to the disclosed structure which performs the function in the illustrated exemplary embodiments of the invention.

While a number of exemplary aspects and embodiments are discussed herein, those of skill in the art will recognize certain modifications, permutations, additions and sub-combinations thereof. For example:

- A number of functionalities are described as applying to each or all of the cross-sections and/or cross-hairs in a concept drawing. This is not absolutely necessary. In some embodiments, the number of cross-sections and/or cross-hairs in a concept drawing can be suitably reduced (e.g. to minimize computational resources used to perform the methods described herein and/or to remove problematic cross-sections and/or cross-hairs which may lead to artifacts). In other embodiments, the methods described herein (and/or some of the steps of the methods described herein) may be practiced over a subset of the available cross-sections or cross-hairs.

It will be appreciated that the description provided herein and the accompanying claims refer to various coordinate system axes and directions. These axes and directions are merely labels and the coordinate system axes and directions may be rotated while remaining within the scope of the invention.

While a number of exemplary aspects and embodiments have been discussed above, those of skill in the art will recognize certain modifications, permutations, additions and sub-combinations thereof. It is therefore intended that the following appended claims and claims hereafter introduced are interpreted to include all such modifications, permutations, additions and sub-combinations as are within their true spirit and scope.

What is claimed is:

1. A computer-implemented method for characterizing a three-dimensional object underlying a two-dimensional concept drawing, the method comprising:

obtaining, at a computer system, a two-dimensional concept drawing comprising a two-dimensional computer representation of a three-dimensional object underlying the concept drawing, the concept drawing comprising a plurality of two-dimensional cross-sections which intersect at one or more cross-hairs and saving the two-dimensional concept drawing in a memory accessible to the computer system;

determining, by the computer system, a three-dimensional vector field computer representation of the three-dimensional object underlying the concept drawing and saving the three-dimensional vector field in the memory accessible to the computer system, the three-dimensional vector field comprising a plurality of three-dimensional vectors;

wherein determining the three-dimensional vector field comprises:

determining, by the computer system, for each cross-section:

a corresponding plane on which the cross-section is located, the plane having a normal vector n in a three-dimensional coordinate system; and

for each cross-hair on the cross-section, a tangent vector t in the three-dimensional coordinate system which is tangent to the cross-section at the cross-hair;

wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, one or more constraints are satisfied, the one or more constraints comprising:

the normal vector n_i of the plane on which the i^{th} cross-section is located is at least approximately orthogonal to the normal vector n_j of the plane on which the j^{th} cross-section is located; and

the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair is at least approximately orthogonal to the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair; and

wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections:

the one or more constraints comprising the normal vector n_i of the plane corresponding to the i^{th} cross-section is at least approximately orthogonal to the normal vector n_j the plane corresponding to the j^{th} cross-section comprises $\|n_i \cdot n_j\| \leq \epsilon$, where ϵ is a positive number close to zero and is a parameter used to accommodate error in the concept drawing; and

the one or more constraints comprising the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair is at least approximately orthogonal to the tangent vector t_{ji} of the j^{th} cross-section at the cross-hair comprises $\|t_{ij} \cdot t_{ji}\| \leq \gamma$, where γ is a positive number close to zero and is a parameter used to accommodate error in the concept drawing.

2. A method according to claim **1** where the concept drawing comprises a two-dimensional silhouette and at least one of the cross-sections intersects the silhouette and the method comprises requiring that a tangent vector to the at least one of the cross-sections at the intersection of the at least one of the cross-sections and the silhouette t_s have a depth component that extends out of a view plane of the concept drawings and toward the viewer in the three-dimensional coordinate system.

3. A method according to claim **1** comprising performing a constrained optimization which comprises minimizing an objective function subject to the one or more constraints to thereby determine, for each cross-section: a normal vector n for the corresponding plane on which the cross-section is located; and, for each cross-hair on the cross-section, a tangent vector t which is tangent to the cross-section at the cross-hair.

4. A method according to claim **1** wherein determining, for each cross-section, the corresponding plane on which the cross-section is located comprises determining, for each plane an offset parameter c_i, the offset parameter c_i representing a location of the plane in the three-dimensional coordinate system.

5. A method according to claim **4** comprising performing a constrained optimization which comprises minimizing an objective function subject to the one or more constraints to thereby determine, for each cross-section:

the corresponding plane on which the cross-section is located, the plane having a normal vector n and an offset parameter c_i; and, for each cross-hair on the cross-section, a tangent vector t which is tangent to the cross-section at the cross-hair.

6. A computer-implemented method for characterizing a three-dimensional object underlying a two-dimensional concept drawing, the method comprising:

obtaining, at a computer system, a two-dimensional concept drawing comprising a two-dimensional computer representation of a three-dimensional object underlying the concept drawing, the concept drawing comprising a plurality of two cross-sections which intersect at one or more cross-hairs and saving the two-dimensional concept drawing in a memory accessible to the computer system;

performing, by the computer system, a constrained optimization and thereby determining a three-dimensional vector field computer representation of the three-dimensional object underlying the concept drawing and saving the three-dimensional vector field in the memory accessible to the computer system, the three-dimensional vector field comprising a plurality of three-dimensional vectors;

wherein determining the three-dimensional vector field comprises:

determining, by the computer system, for each cross-section:

a corresponding plane on which the cross-section is located, the plane having a normal vector n in a three-dimensional coordinate system; and

for each cross-hair on the cross-section, a tangent vector t in the three-dimensional coordinate system which is tangent to the cross-section at the cross-hair;

wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections one or more constraints are satisfied, the one or more constraints comprising:

the normal vector n_i of the plane on which the i^{th} cross-section is located is at least approximately orthogonal to the normal vector n_j of the plane on which the j^{th} cross-section is located; and

the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair is at least approximately orthogonal to the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair; and

wherein performing the constrained optimization comprises minimizing an objective function subject to the one or more constraints to thereby determine, for each cross-section: the normal vector n for the corresponding plane on which the cross-section is located; and, for each cross-hair on the cross-section, the tangent vector t which is tangent to the cross-section at the cross-hair;

wherein the objective function comprises a function of a local geodesic term, the local geodesic term minimized when, for each cross-hair between i^{th} and j^{th} cross-sections, at least one of the i^{th} and j^{th} cross-sections is a local geodesic so that the normal vector n of the plane on which the local geodesic cross-section is located is collinear with tangent vector t which is tangent to the cross-section that intersects with the local geodesic cross-section.

7. A computer-implemented method for characterizing a three-dimensional object underlying a two-dimensional concept drawing, the method comprising:

obtaining, at a computer system, a two-dimensional concept drawing comprising a two-dimensional computer representation of a three-dimensional object underlying the concept drawing, the concept drawing comprising a plurality of two-dimensional cross-sections which intersect at one or more cross-hairs and saving the two-dimensional concept drawing in a memory accessible to the computer system;

performing, by the computer system, a constrained optimization and thereby determining a three-dimensional vector field computer representation of the three-dimensional object underlying the concept drawing and saving the three-dimensional vector field in the memory accessible to the computer system, the three-dimensional vector field comprising a plurality of three-dimensional vectors;

wherein determining the three-dimensional vector field comprises:

determining, by the computer system, for each cross-section:

a corresponding plane on which the cross-section is located, the plane having a normal vector n in a three-dimensional coordinate system; and

for each cross-hair on the cross-section, a tangent vector t in the three-dimensional coordinate system which is tangent to the cross-section at the cross-hair;

wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections one or more constraints are satisfied, the one or more constraints comprising:

the normal vector n_i of the plane on which the i^{th} cross-section is located is at least approximately orthogonal to the normal vector n_j of the plane on which the j^{th} cross-section is located; and

the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair is at least approximately orthogonal to the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair; and

wherein performing the constrained optimization comprises minimizing an objective function subject to the one or more constraints to thereby determine, for each cross-section: the normal vector n for the corresponding plane on which the cross-section is located; and for each cross-hair on the cross-section, the tangent vector t which is tangent to the cross-section at the cross-hair;

wherein the objective function comprises a function of a minimal foreshortening term, the minimal foreshortening term is minimized when foreshortening of the tangent vectors t in directions orthogonal to a view plane of the concept drawing is minimized over the concept drawing.

8. A computer-implemented method for characterizing a three-dimensional object underlying a two-dimensional concept drawing, the method comprising:

obtaining, at a computer system a two-dimensional concept drawing comprising a two-dimensional computer representation of a three-dimensional object underlying the concept drawing, the concept drawing comprising a plurality of two-dimensional cross-sections which intersect at one or more cross-hairs and saving the two-dimensional concept drawing in a memory accessible to the computer system;

performing, by the computer system, a constrained optimization and thereby determining a three-dimensional vector field computer representation of the three-dimensional object underlying the concept drawing and saving the three-dimensional vector field in the memory accessible to the computer system, the three-dimensional vector field comprising a plurality of three-dimensional vectors;

wherein determining the three-dimensional vector field comprises:

determining, by the computer system, for each cross-section:

a corresponding plane on which the cross-section is located, the plane having a normal vector n in a three-dimensional coordinate system; and

for each cross-hair on the cross-section, a tangent vector t in the three-dimensional coordinate system which is tangent to the cross-section at the cross-hair;

wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, one or more constraints are satisfied, the one or more constraints comprising:

the normal vector n_i of the plane on which the i^{th} cross-section is located is at least approximately orthogonal to the normal vector n_j of the plane on which the j^{th} cross-section is located; and

the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair is at least approximately orthogonal to the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair; and

wherein performing the constrained optimization comprises minimizing an objective function subject to the one or more constraints to thereby determine, for each cross-section: the normal vector n for the corresponding plane on which the cross-section is located; and, for each cross-hair on the cross-section, the tangent vector t which is tangent to the cross-section at the cross-hair;

wherein the objective function comprises a function f of the form:

$$f(|t_{ij}\times n_j|,|t_{ji}\times n_i|,(t_{ij}^{z})^2+(t_{ji}^{z})^2$$

evaluated at each cross-hair comprising i^{th} and j^{th} intersecting cross-sections in the concept drawing, t_{ij} and t_{ji} are tangent vectors of the i^{th} and j^{th} cross-sections at a given cross-hair, t_{ij}^{z} and t_{ji}^{z} are respectively the components of the tangent vectors t_{ij} and t_{ji} in a z-direction orthogonal to a view plane of the concept drawing and n_i and n_j are normal vectors of the planes on which the cross-sections intersecting at the given cross-hair are located.

9. A computer-implemented method for characterizing a three-dimensional object underlying a two-dimensional concept drawing, the method comprising:

obtaining, at a computer system, a two-dimensional concept drawing comprising a two-dimensional computer representation of a three-dimensional object underlying the concept drawing, the concept drawing comprising a plurality of two-dimensional cross-sections which intersect at one or more cross-hairs and saving the two-dimensional concept drawing in a memory accessible to the computer system;

performing, by the computer system, a constrained optimization and thereby determining a three-dimensional vector field computer representation of the three-dimensional object underlying the concept drawing and saving the three-dimensional vector field in the memory accessible to the computer system, the three-dimensional vector field comprising a plurality of three-dimensional vectors;

wherein determining the three-dimensional vector field comprises:

determining, by the computer system, for each cross-section:

a corresponding plane on which the cross-section is located, the plane having a normal vector n in a three-dimensional coordinate system; and

for each cross-hair on the cross-section, a tangent vector t in the three-dimensional coordinate system which is tangent to the cross-section at the cross-hair;

wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, one or more constraints are satisfied, the one or more constraints comprising:

the normal vector n_i of the plane on which the i^{th} cross-section is located is at least approximately orthogonal to the normal vector n_j of the plane on which the j^{th} cross-section is located; and

the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair is at least approximately orthogonal to the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair; and

wherein performing the constrained optimization comprises minimizing an objective function subject to the one or more constraints to thereby determine, for each cross-section: the normal vector n for the corresponding plane on which the cross-section is located; and, for each cross-hair on the cross-section, the tangent vector t which is tangent to the cross-section at the cross-hair;

wherein the objective function comprises:

$$\Sigma_{ij}a_{ij}\|t_{ij}\times n_j\|^2+b_{ij}\|t_{ji}\times n_i\|^2+d_{ij}[(t_{ij}^{z})^2+(t_{ji}^{z})^2]$$

where the sum over ij represents the sum over the cross-hairs comprising i^{th} and j^{th} intersecting cross-sections in the concept drawing, t_{ij} and t_{ji} are tangent vectors of the i^{th} and j^{th} cross-sections at a given cross-hair, t_{ij}^{z} and t_{ji}^{z} are respectively the components of the tangent vectors t_{ij} and t_{ji} in a z-direction orthogonal to a view plane of the concept drawing, n_i and n_j are normal vectors of the planes on which the cross-sections intersecting at the given cross-hair are located, and a_{ij}, b_{ij}, and d_{ij} represent weighting coefficients.

10. A method according to claim **1** wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, the one or more constraints comprise: the normal vector n_i of the plane on which the i^{th} cross-section is located is orthogonal to the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair.

11. A computer implemented method for characterizing a three-dimensional object underlying a two-dimensional concept drawing, the method comprising:

obtaining, at a computer system, a two-dimensional concept drawing comprising a two-dimensional computer representation of a three-dimensional object underlying the concept drawing, the concept drawing comprising a plurality of two-dimensional cross-sections which intersect at one or more cross-hairs and saving the two-dimensional concept drawing in a memory accessible to the computer system;

determining, by the computer system, a three-dimensional vector field computer representation of the three-dimensional object underlying the concept drawing and saving the three-dimensional vector field in the memory accessible to the computer system, the three-dimensional vector field comprising a plurality of three-dimensional vectors;

wherein determining the three-dimensional vector field comprises:

determining, by the computer system, for each cross-section:

a corresponding plane on which the cross-section is located, the plane having a normal vector n in a three-dimensional coordinate system; and

for each cross-hair on the cross-section, a tangent vector t in the three-dimensional coordinate system which is tangent to the cross-section at the cross-hair;

wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, one or more constraints are satisfied, the one or more constraints comprising:

the normal vector n_i of the plane on which the i^{th} cross-section is located is at least approximately orthogonal to the normal vector n_j of the plane on which the j^{th} cross-section is located; and

the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair is at least approximately orthogonal to the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair;

wherein determining, for each cross-section, the corresponding plane on which the cross-section is located comprises determining, for each plane an offset parameter c_i, the offset parameter c_i representing a location of the plane in the three-dimensional coordinate system; and

wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, the one or more constraints comprise:

$$x_x(n_i^{x}-n_j^{x})+x_y(n_i^{y}-n_j^{y})+(c_i-c_j)=0$$

where:

x_x and x_y are coordinates of the cross-hair in first and second directions parallel to a view plane of the concept drawing;

n_i^{x} and n_j^{x} are magnitudes of the normal vectors of the i^{th} and j^{th} cross-sections, respectively, in the first direction;

n_i^{y} and n_j^{y} are magnitudes of the normal vectors of the i^{th} and j^{th} cross-sections, respectively, in the second direction; and

c_i and c_j are offset values representing locations of the planes on which the i^{th} and j^{th} cross-sections are located.

12. A method according to claim **1** wherein determining, for each cross-section and for each cross-hair on the cross-section, toe tangent vector t comprises, if multiple tangent vectors t satisfy the constraints of the method, selecting values for the tangent vectors t which are consistent with the view from above.

13. A method according to claim **1** wherein determining the three-dimensional vector field further comprises, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, generating a corresponding cross-hair surface normal vector n_{ij} characterizing a surface of an object underlying the concept drawing in the three-dimensional coordinate system, wherein generating the corresponding cross-hair surface normal vector is based on the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair and the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair.

14. A method according to claim **13** wherein determining the three-dimensional vector field further comprises propagating the cross-hair surface normal vectors to locations away from the cross-hairs.

15. A method according to claim **14** wherein propagating the cross-hair surface normal vectors comprises, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, generating a plurality of cross-section surface normal vectors along at least a portion of the i^{th} and j^{th} cross-sections, the cross-section surface normal vectors based at least in part on one or more of: the corresponding cross-hair surface normal vector n_{ij}, the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair and the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair.

16. A computer-implemented method for characterizing a three-dimensional object underlying a two-dimensional concept drawing, the method comprising:

obtaining, at a computer system, a two-dimensional concept drawing comprising a two-dimensional computer representation of a three-dimensional object underlying the concept drawing, the concept drawing comprising a plurality of two-dimensional cross-sections which intersect at one or more cross-hairs and saving the two-dimensional concept drawing in a memory accessible to the computer system;

determining, by the computer system, a three-dimensional vector field computer representation of the three-dimensional object underlying the concept drawing and saving the three-dimensional vector field in the memory accessible to the computer system, the three-dimensional vector field comprising a plurality of three-dimensional vectors;

wherein determining the three-dimensional vector field comprises:

determining, by the computer system, for each cross-section:

a corresponding plane on which the cross-section is located, the plane having a normal vector n in a three-dimensional coordinate system; and

for each cross-hair on the cross-section, a tangent vector t in the three-dimensional coordinate system which is tangent to the cross-section at the cross-hair;

wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, one or more constraints are satisfied, the one or more constraints comprising:

the normal vector n_i of the plane on which the i^{th} cross-section is located is at least approximately orthogonal to the normal vector n_j of the plane on which the j^{th} cross-section is located; and

the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair is at least approximately orthogonal to the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair;

wherein determining the three-dimensional vector field further comprises:

for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, generating a corresponding cross-hair surface normal vector n_{ij} characterizing a surface of an object underlying the concept drawing in the three-dimensional coordinate system, wherein generating the corresponding cross-hair surface normal vector is based on the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair and the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair; and

propagating the cross-hair surface normal vectors to locations away from the cross-hairs, wherein propagating the cross-hair surface normal vectors comprises, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, generating a plurality of cross-section surface normal vectors alone at least a portion of the i^{th} and j^{th} cross-sections, the cross-section surface normal vectors based at least in part on one or more of: the corresponding cross-hair surface normal vector n_{ij}, the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair and the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair;

wherein generating the plurality of cross-section surface normal vectors comprises, at a location x away from a first cross-hair along a first cross-section intersecting the first cross-hair:

determining a first tangent vector t_{ax} tangent to the first cross-section at the location x and coplanar with the plane in which the first cross-section is located;

determining a second tangent vector t_{xa} at the location x based at least in part on a third tangent vector t_{ba}, the third tangent vector t_{ba} tangent to a second cross-section intersecting with the first cross-section at the first cross-hair and coplanar with the plane in which the second cross-section is located; and

generating a cross-section surface normal vector for the location x, the cross-section surface normal orthogonal to the first and second tangent vectors.

17. A method according to claim **16** wherein determining the second tangent vector t_{xa} comprises according to an arc-length-based weighted average of the third tangent vector t_{ba} and a fourth tangent vector t_{ca}, the fourth tangent vector t_{ca} tangent to a third cross-section intersecting the first cross-section at a second cross-hair and coplanar with the plane in which the third cross-hair is located.

18. A method according to claim **17** wherein the second tangent vector t_{xa} determined according to:

$$t_{xa} = \frac{\sigma t_{ba} + \psi t_{ca}}{\Psi + \sigma}$$

where Ψ is an arc length along the first cross-section between the first cross-hair and the location x, and σ is an arc length along the first cross-section between the second cross-hair and the location x.

19. A computer implemented method for characterizing a three-dimensional object underlying a two-dimensional concept drawing, the method comprising:

obtaining, at a computer system, a two-dimensional concept drawing comprising a two-dimensional computer representation of a three-dimensional object underlying the concept drawing, the concept drawing comprising a plurality of two-dimensional cross-sections which intersect at one or more cross-hairs and saving the two-dimensional concept drawing in a memory accessible to the computer system;

determining, by the computer system, a three-dimensional vector field computer representation of the three-dimensional object underlying the concept drawing and saving the three-dimensional vector field in the memory accessible to the computer system, the three-dimensional vector field comprising a plurality of three-dimensional vectors;

wherein determining the three-dimensional vector field comprises:

determining, by the computer system, for each cross-section:

a corresponding plane on which the cross-section is located, the plane having a normal vector n in a three-dimensional coordinate system; and

for each cross-hair on the cross-section, a tangent vector t in the three-dimensional coordinate system which is tangent to the cross-section at the cross-hair;

wherein, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, one or more constraints are satisfied, the one or more constraints comprising:

the normal vector n_i of the plane on which the i^{th} cross-section is located is at least approximately orthogonal to the normal vector n_j of the plane on which the j^{th} cross-section is located; and

the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair is at least approximately orthogonal to the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair;

wherein determining the three-dimensional vector field further comprises:

for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, generating a corresponding cross-hair surface normal vector n_{ij} characterizing a surface of an object underlying the concept drawing in the three-dimensional coordinate system, wherein generating the corresponding cross-hair surface normal vector is based on the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair and the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair; and

propagating the cross-hair surface normal vectors to locations away from the cross-hairs, wherein propagating the cross-hair surface normal vectors comprises, for each cross-hair comprising i^{th} and j^{th} intersecting cross-sections, generating a plurality of cross-section surface normal vectors along at least a portion of the i^{th} and j^{th} cross-sections, the cross-section surface normal vectors based at least in part on one or more of: the corresponding cross-hair surface normal vector n_{ij}, the tangent vector t_{ij} to the i^{th} cross-section at the cross-hair and the tangent vector t_{ji} to the j^{th} cross-section at the cross-hair; and

wherein the method further comprises defining one or more regions of the concept drawing, each of the regions bounded by a plurality of curves, each curve being one of: a cross-section and a boundary curve; and wherein propagating the cross-hair surface normal vectors comprises propagating the cross-section surface normal vectors to an interior of the one or more regions.

20. A method according to claim **19** wherein defining one or more regions of the concept drawing comprises defining each region to be bounded by four curves and wherein propagating the cross-section surface normal vectors to the interior of the one or more regions comprises, for each region: where any of the four curves that define the region are not cross-sections, estimating surface normal vectors on such curves based on the cross-section surface normal vectors of one or more proximate cross-sections; and performing Coons patches interpolation to obtain surface normal vectors in the interior of the region.

21. A method according to claim **1** wherein determining the three-dimensional vector field further comprises: generating a plurality of surface normal vectors characterizing an object underlying the concept drawing in the three-dimensional coordinate system, generating the plurality of surface normal vectors based at least in part on one or more of: one or more of the normal vectors n and one or more of the tangent vectors t.

22. A method according to claim **21** comprising shading the concept drawing based at least in part on the plurality of surface normal vectors.

23. A computer program product comprising a set of instructions embodied on a non-transitory computer readable medium, the instructions when executed by a processor, cause the processor to perform the steps of method 1.

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